Lecture 10

Frequency response

topics

- Bode diagram
- BJT's Frequency response
- MOSFET Frequency response

$$v_i(t) = V_i \sin \omega t \qquad v_o(t) = V_o \sin(\omega t + \phi)$$

Magnitude: $\dfrac{V_o}{V_i}$ Phase: ϕ

$$T(s) = \frac{V_o(s)}{V_i(s)} \qquad s = \sigma + j\omega \Rightarrow s = j\omega$$

Steady-state response

$$T(\omega) = \frac{V_o(\omega)}{V_i(\omega)}$$

Magnitude: $\dfrac{|V_o(j\omega)|}{|V_i(j\omega)|}$ Phase: $\dfrac{\angle V_o(j\omega)}{\angle V_i(j\omega)}$

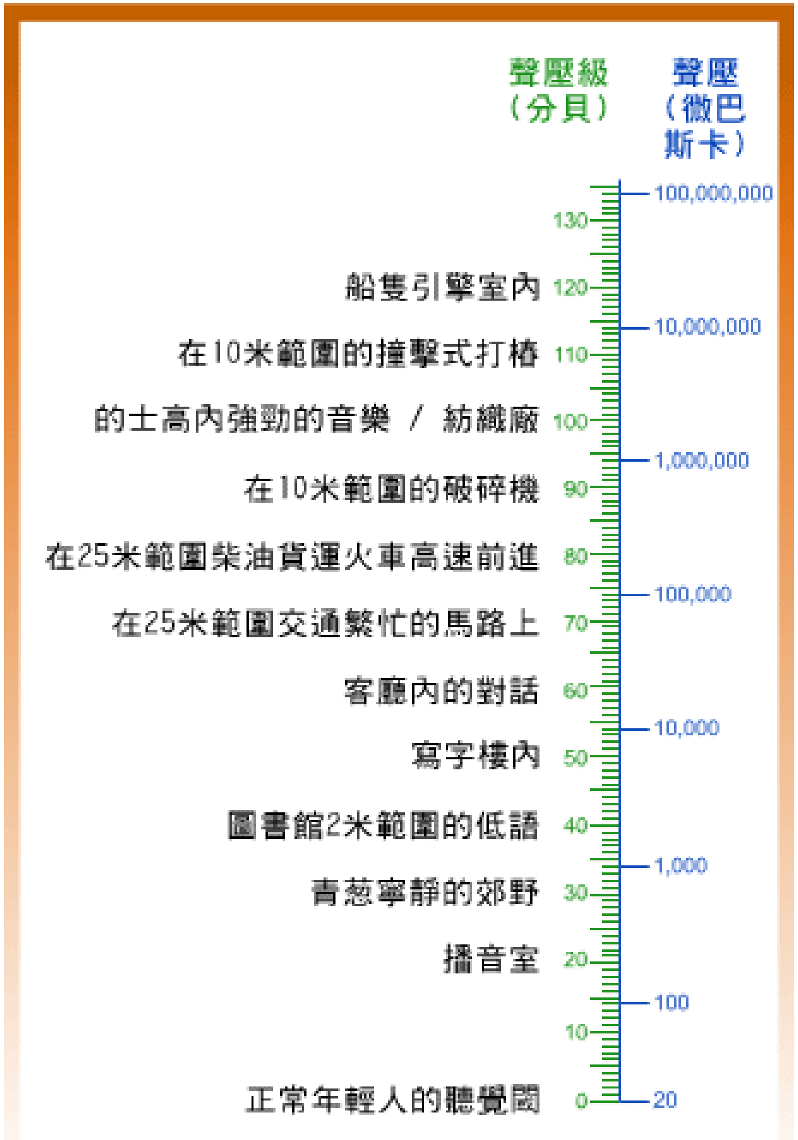
dB (decibel)= Decimal + Bell

$$dB \equiv 10\log_{10}\frac{p_1}{p_2}$$

$$\because\ p = i^2 z = \frac{v^2}{z}$$

$$\Rightarrow dB = 20\log_{10}\frac{v_1}{v_2} = 20\log_{10}\frac{i_1}{i_2}$$

Human hearing frequency zone : 10Hz~24kHz
Most Sensitive frequency zone : 2kHz~5kHz



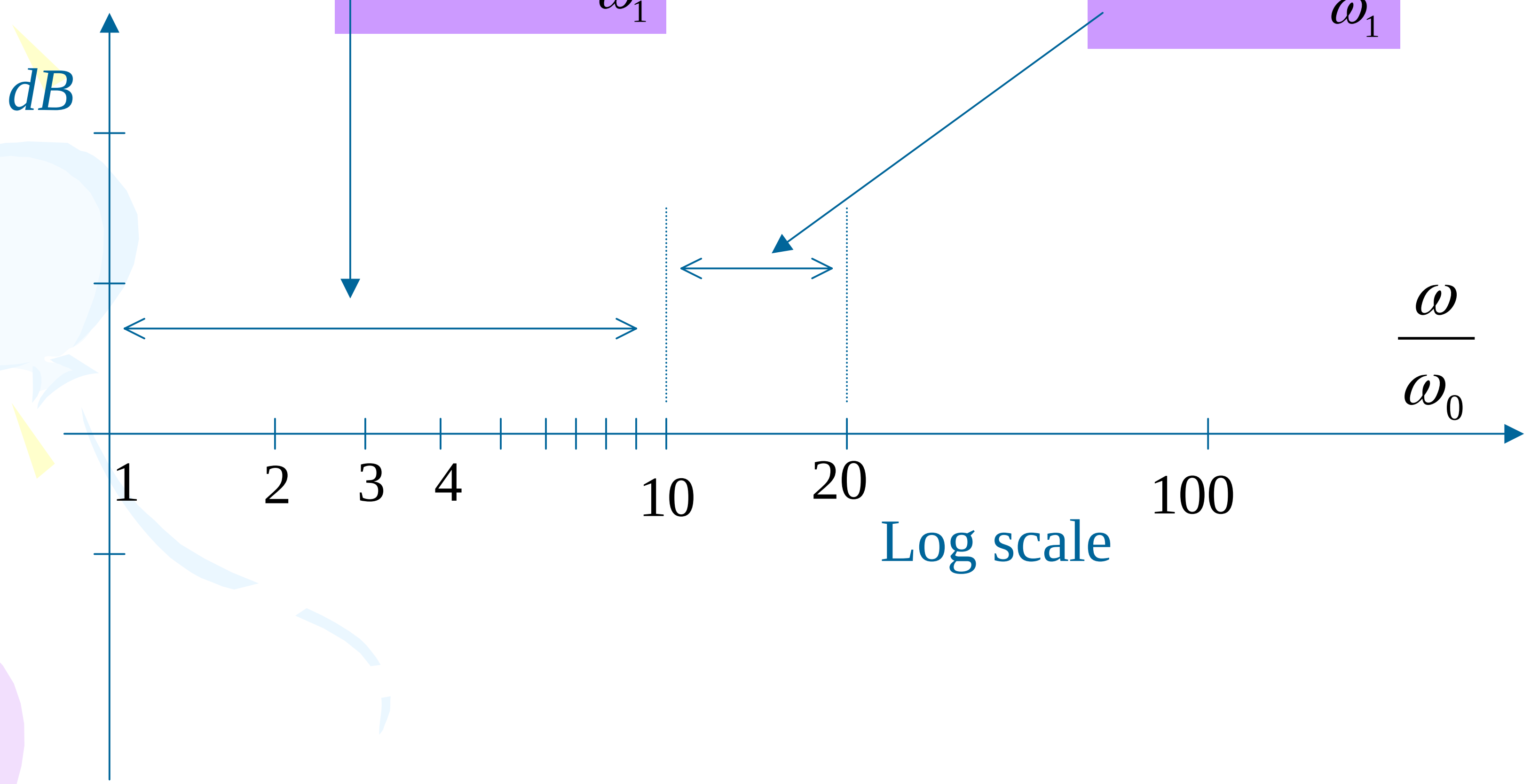
聲壓級(分貝)和聲壓(微巴斯卡)的比對表

圖表來自http://www.epd.gov.hk/epd/noise_education/web/CHI_EPD_HTML/m1/intro_5.html

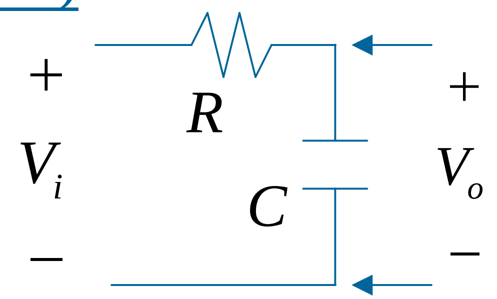
Logarithmic coordinate

Decade : $dec = \log_{10} \frac{\omega_2}{\omega_1}$

Octave : $oct = \log_2 \frac{\omega_2}{\omega_1}$



Example(low pass)



$$V_o = \frac{1/sC}{R + 1/sC} V_i \Rightarrow T(\omega) = \frac{1}{1 + (j\omega)RC}$$

$$let \quad \omega_0 = \frac{1}{RC} \Rightarrow T(\omega) = \frac{1}{1 + (j\omega)RC} = \frac{1}{1 + (\frac{j\omega}{\omega_0})}$$

$$if \quad \omega = \omega_0 \Rightarrow |T(\omega)| = \frac{1}{\sqrt{2}}$$

$$\Rightarrow \angle T(\omega) = 0 - \tan^{-1} 1 = -45^0$$

$$T(\omega)=\frac{1}{1+(\frac{s}{\omega_0})}=\frac{1}{1+(\frac{j\omega}{\omega_0})}$$

Magnitude:

$$\left|(1+j\frac{\omega}{\omega_0})^{-1}\right|_{dB}=-20\log\sqrt{1+(\frac{\omega}{\omega_0})^2}$$

$$=-10\log[1+(\frac{\omega}{\omega_0})^2]$$

$$\omega<<\omega_0\Rightarrow\frac{\omega}{\omega_0}\approx 0$$

$$\Rightarrow dB=-10\log 1=0$$

$$\omega>>\omega_0\Rightarrow 1+j\frac{\omega}{\omega_0}\approx\frac{\omega}{\omega_0}$$

$$\Rightarrow dB\approx -20\log\frac{\omega}{\omega_0}$$

$$dB=-[20\log\omega-20\log\omega_0]$$

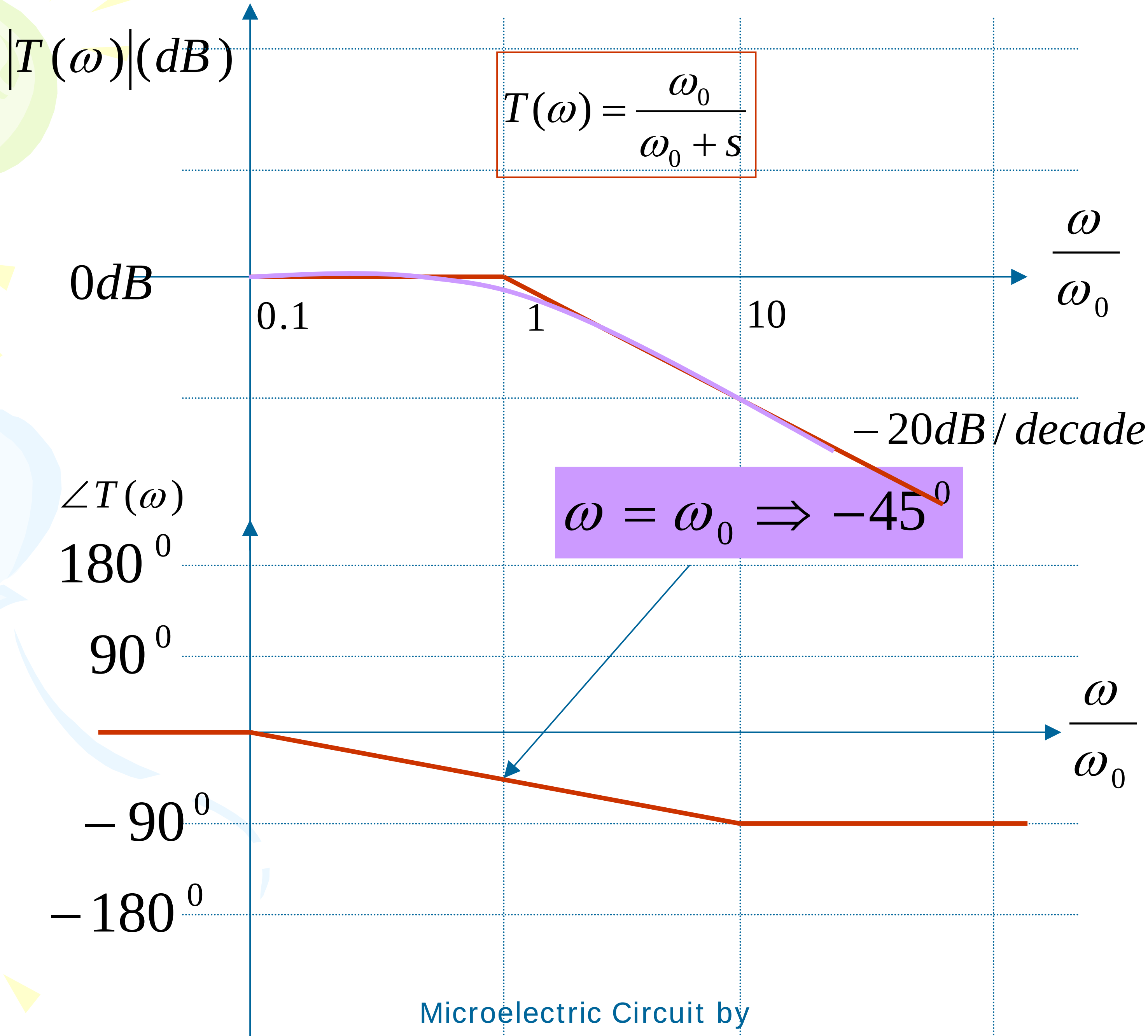
$$\omega=\omega_0\Rightarrow 1+j1\Rightarrow dB=-10\log 2=-3.01$$

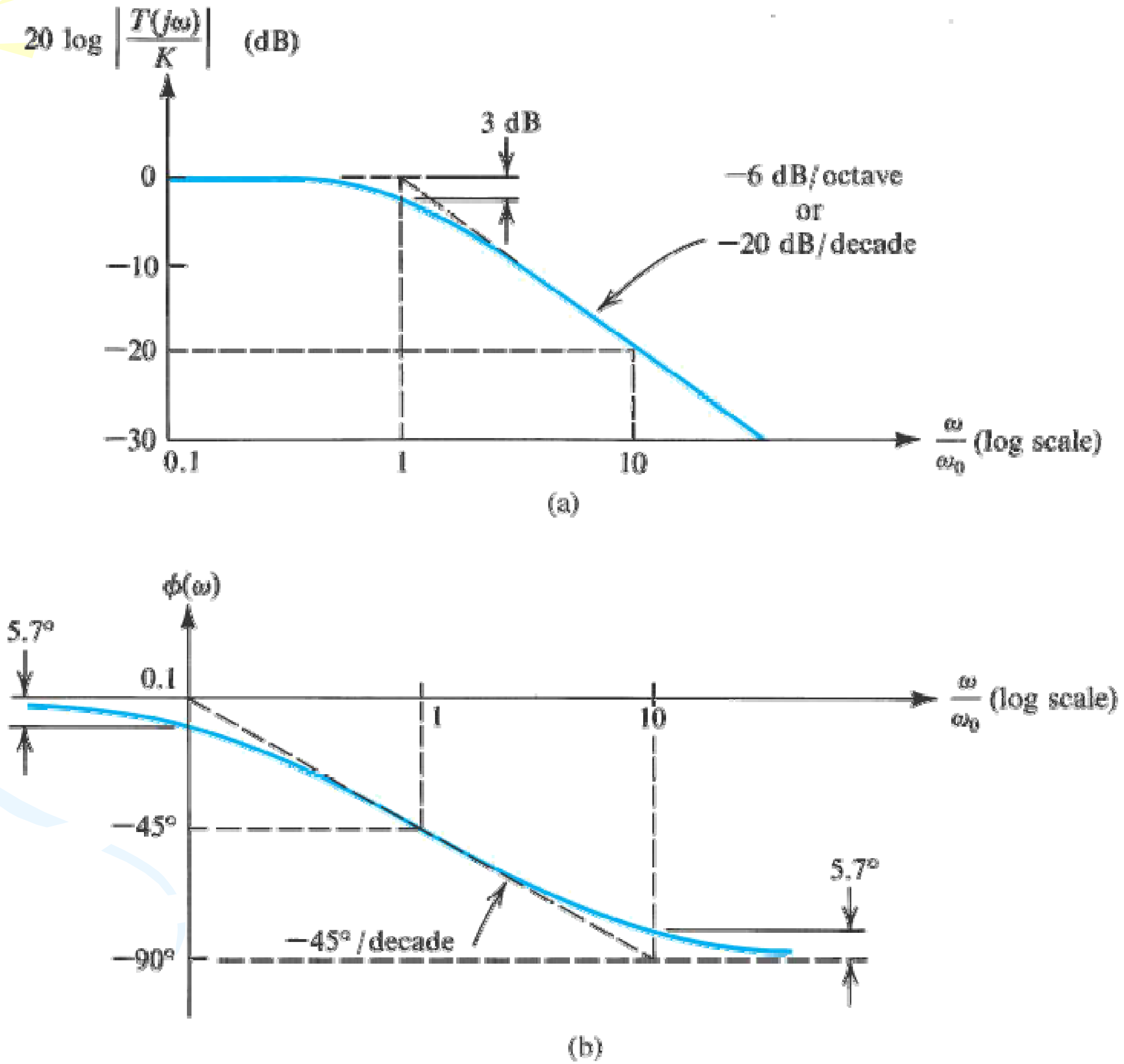
Phase:

$$\angle(1+j\frac{\omega}{\omega_0})=0^0-\tan^{-1}\frac{\omega}{\omega_0}$$

$$\omega<<\omega_0\Rightarrow\frac{\omega}{\omega_0}\approx 0\Rightarrow\angle T(\omega)\approx\tan^{-1}0=0^o$$

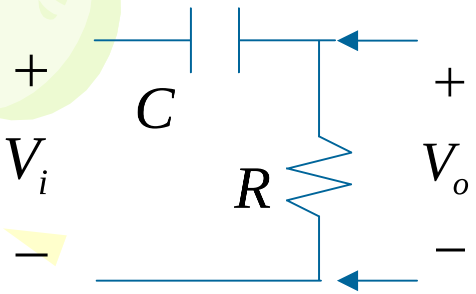
$$\omega>>\omega_0\Rightarrow\frac{\omega}{\omega_0}\approx\infty\Rightarrow\angle T(\omega)\approx-\tan^{-1}\infty=-90^o$$


$|T(\omega)|(dB)$
$T(\omega)=\frac{\omega_0}{\omega_0+s}$
$\frac{\omega}{\omega_0}$
0dB
0.1
1
10
$-20dB/decade$
$\angle T(\omega)$
180^0
90^0
$\omega=\omega_0 \Rightarrow -45^0$
$\frac{\omega}{\omega_0}$
-90^0
-180^0



20 log |T(jω)/K| (dB)
3 dB
0
−10
−20
−30
0.1
1
10
−6 dB/octave
or
−20 dB/decade
ω/ω0 (log scale)
(a)
φ(ω)
5.7°
0.1
1
10
ω/ω0 (log scale)
−45°
5.7°
−45°/decade
−90°
(b)

Example(high pass)



$$V_o = \frac{R}{R + \frac{1}{sC}} V_i \Rightarrow T(\omega) = \frac{j\omega RC}{1 + (j\omega)RC}$$

$$let \quad \omega_0 = \frac{1}{RC} \Rightarrow T(\omega) = \frac{j\omega RC}{1 + (j\omega)RC} = \frac{(\frac{j\omega}{\omega_0})}{1 + (\frac{j\omega}{\omega_0})}$$

$$if \quad \omega = \omega_0 \Rightarrow |T(\omega)| = \frac{1}{\sqrt{2}}$$

$$\Rightarrow \angle T(\omega) = 90 - \tan^{-1} 1 = 45^0$$

$$T(s)=\frac{s}{s+\omega_0} \qquad T(\omega)=\frac{j\omega}{j\omega+\omega_0}$$

Magnitude:

$$\left|\frac{j\omega}{j\omega+\omega_0}\right|_{dB} = 20\log\omega - 20\log\sqrt{\omega^2+\omega_0^2}$$

$$= 20\log\omega - 10\log[\omega^2+\omega_0^2]$$

$$\omega \gg \omega_0 \Rightarrow 20\log\frac{1}{1+\frac{\omega_0}{j\omega}}$$

$$\Rightarrow -20\log(1+\tfrac{\omega_0}{j\omega})$$

$$\Rightarrow dB = -20\log 1 = 0$$

$$\omega \ll \omega_0 \Rightarrow dB \approx 20\log\frac{\omega}{\omega_0}$$

$$dB = 20\log\omega - 20\log\omega_0$$

$$\omega = 0.1\omega_0 \Rightarrow dB = 20\log 0.1 = -20$$

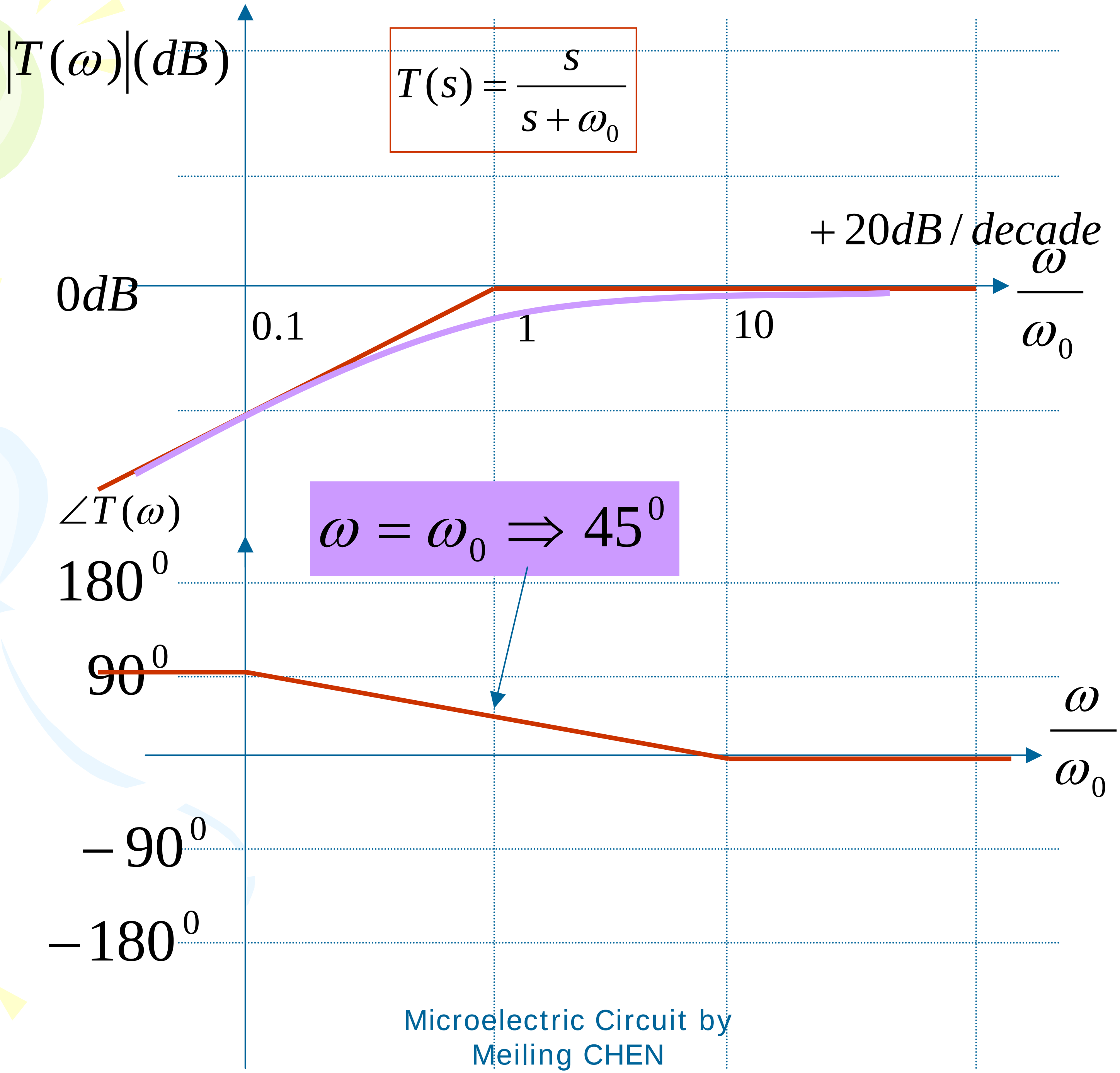
$$\omega = \omega_0 \Rightarrow \frac{1}{1+j1} \Rightarrow dB = -20\log\sqrt{2} = -3.01$$

Phase:

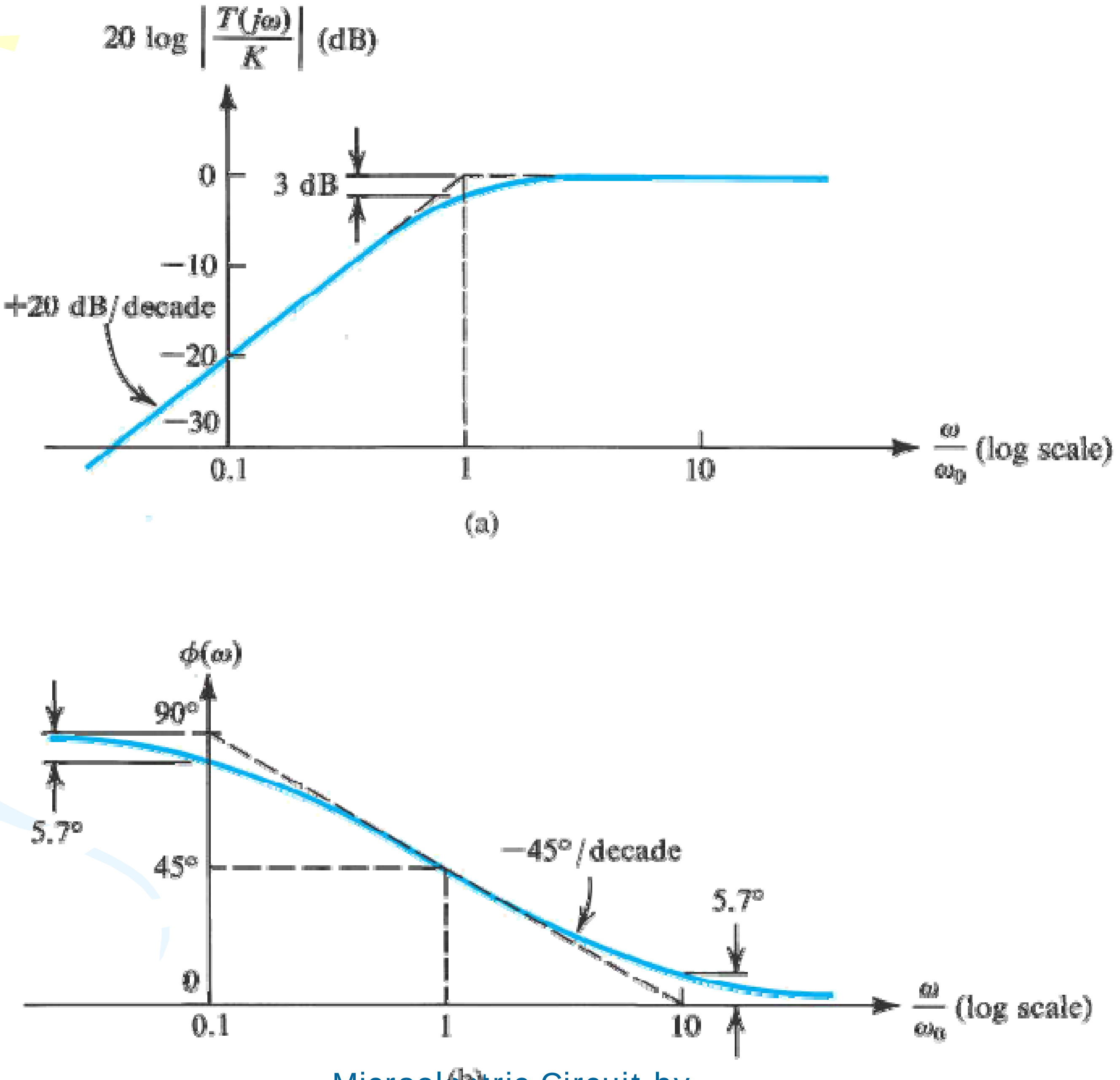
$$\angle\frac{j\omega}{j\omega+\omega_0} = 90 - \tan^{-1}\frac{\omega}{\omega_o}$$

$$\omega \gg \omega_0 \Rightarrow \frac{\omega}{\omega_0} \approx \infty \Rightarrow \angle T(\omega) \approx 90 - \tan^{-1}\infty = 0^o$$

$$\omega \ll \omega_0 \Rightarrow \frac{\omega}{\omega_0} \approx 0 \Rightarrow \angle T(\omega) \approx 90 - \tan^{-1} 0 = 90^o$$



$|T(\omega)|(dB)$
$T(s) = \dfrac{s}{s+\omega_0}$
$+20dB/decade$
$0dB$
0.1
1
10
$\dfrac{\omega}{\omega_0}$
$\angle T(\omega)$
$\omega = \omega_0 \Rightarrow 45^0$
180^0
90^0
$\dfrac{\omega}{\omega_0}$
-90^0
-180^0


20 log |T(jω)/K| (dB)
0
3 dB
−10
+20 dB/decade
−20
−30
0.1
1
10
ω/ω₀ (log scale)
(a)
φ(ω)
90°
5.7°
45°
−45°/decade
5.7°
0
0.1
1
10
ω/ω₀ (log scale)
(b)

$$dB \equiv 20\log|T(\omega)|$$

The bandwidth represents the distance between the two points in the frequency domain where the signal is $1/\sqrt{2}$ of the maximum signal strength.

$$20\log|T(\omega)|$$

$$if \quad |T(\omega)| = \frac{1}{\sqrt{2}}$$

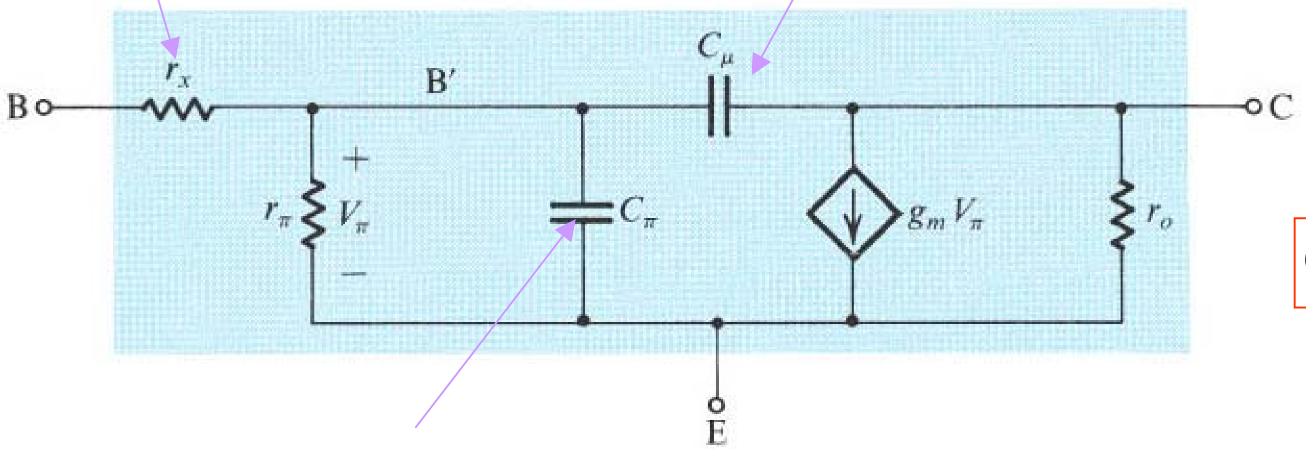
$$if \quad \omega = \omega_0 \Rightarrow |T(\omega)| = \frac{1}{\sqrt{2}}$$

$$\Rightarrow 20\log|T(\omega)| = 10\log 2 = 3dB$$

BJT high frequency model

Splitting resistance (refinement the lumped-component circuit)

Depletion capacitance



$$C_\pi >> C_\mu$$

Emitter-base capacitance
= diffusion capacitance + Base-Emitter junction capacitance

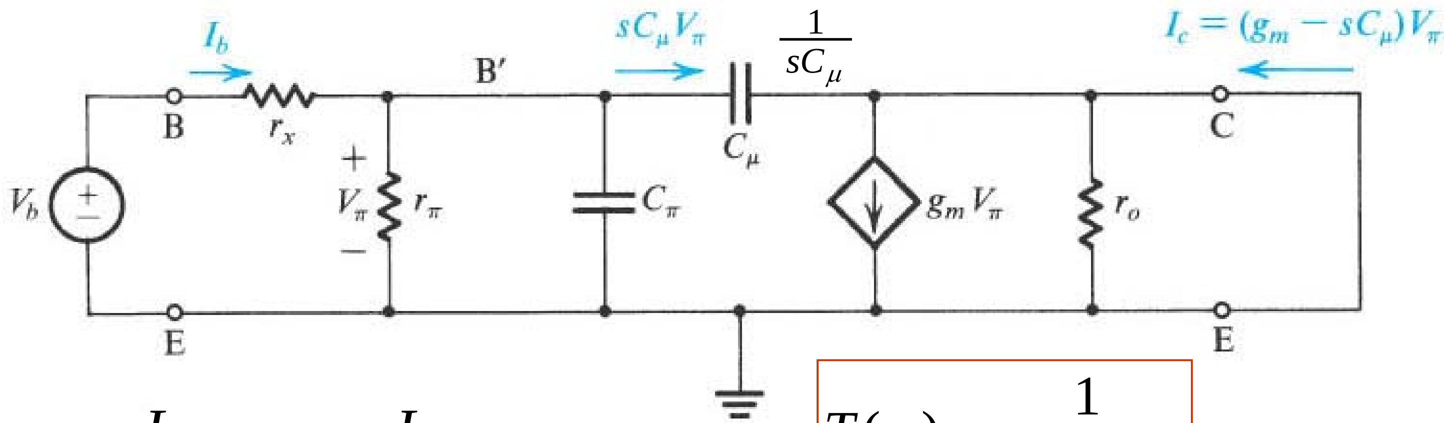
KTC9013 Technical data

ELECTRICAL CHARACTERISTICS (Ta=25℃)

CHARACTERISTIC	SYMBOL	TEST CONDITION	MIN.	TYP.	MAX.	UNIT
Collector Cut-off Current	I_{CBO}	V_{CB}=35V, I_E=0	-	-	0.1	μA
Emitter Cut-off Current	I_{EBO}	V_{EB}=5V, I_C=0	-	-	0.1	μA
DC Current Gain	h_{FE}(Note)	V_{CE}=1V, I_C=50mA	64	-	246	
Collector-Emitter Saturation Voltage	$V_{CE(sat)}$	I_C=100mA, I_B=10mA	-	0.1	0.25	V
Base-Emitter Voltage	V_{BE}	I_C=100mA, V_{CE}=1V	-	0.8	1.0	V
Transition Frequency	f_T	V_{CE}=6V, I_C=20mA, f=100MHz	140	-	-	MHz
Collector Output Capacitance	C_{ob}	V_{CB}=6V, I_E=0, f=1MHz	-	7.0	-	pF

Note : h_{FE} Classification D:64~91, E:78~112, F:96~135, G:118~166, H:144~202, I:176~246

How to find C_π by datasheet ?



$$T(\omega) = \frac{1}{1+(\frac{s}{\omega_0})}$$

$$h_{fe} \equiv \frac{I_c}{I_b} \Leftrightarrow \beta = \frac{I_C}{I_B}$$

$$I_c = g_m V_\pi - \frac{V_\pi}{1/sC_\mu} = (g_m - sC_\mu)V_\pi$$

3-dB frequency

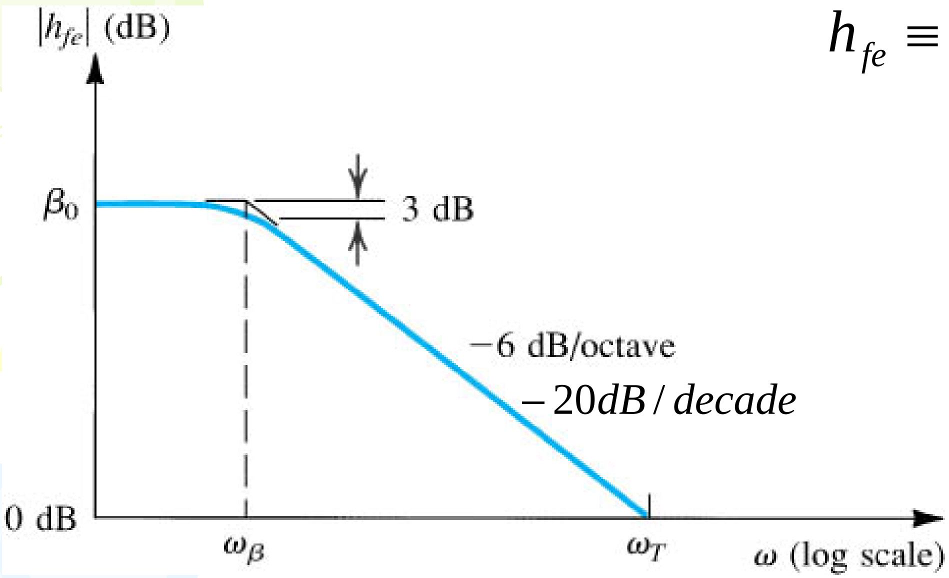
$$\omega_\beta = \frac{1}{(C_\pi + C_\mu)r_\pi}$$

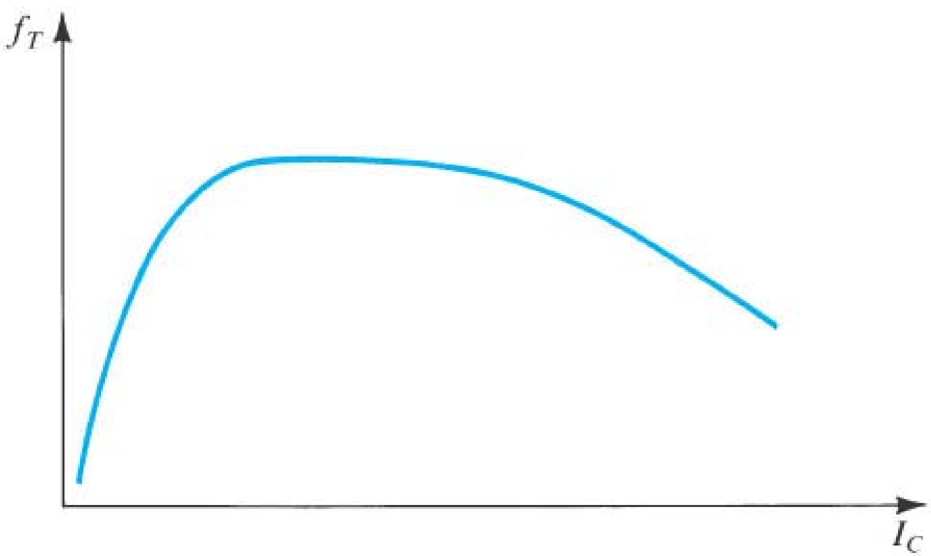
$$I_b = \frac{V_\pi}{(r_\pi // C_\pi // C_\mu)}$$

$$h_{fe} \equiv \frac{I_c}{I_b} = \frac{g_m - sC_\mu}{1/r_\pi + s(C_\pi + C_\mu)}$$

Low frequency ß

$$\Rightarrow h_{fe} \approx \frac{g_m r_\pi}{1+s(C_\pi + C_\mu)r_\pi} = \frac{\beta_0}{1+s(C_\pi + C_\mu)r_\pi}$$





$$h_{fe} \equiv \frac{I_c}{I_b} = \frac{\beta_0}{1+s(C_\pi + C_\mu)r_\pi} \Leftrightarrow \frac{1}{1+s/\omega_\beta}$$

$$20\log\beta - 20\log\sqrt{1+(\omega_T/\omega_\beta)^2} = 0$$

$$\beta = \sqrt{1+(\omega_T/\omega_\beta)^2}$$

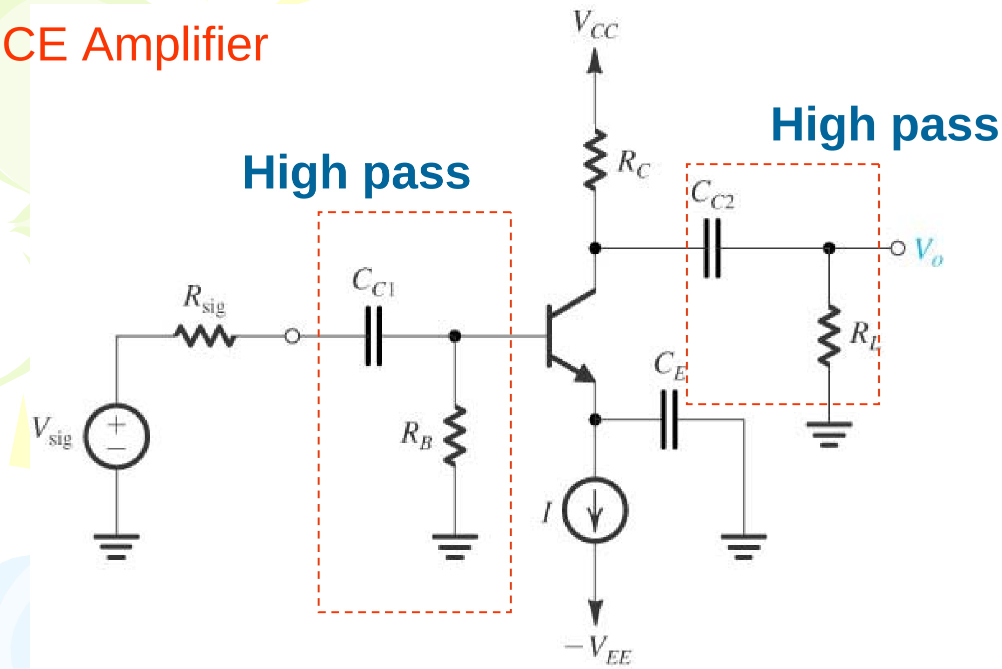
$$\omega_T \approx \omega_\beta \beta \because \beta >> 1$$

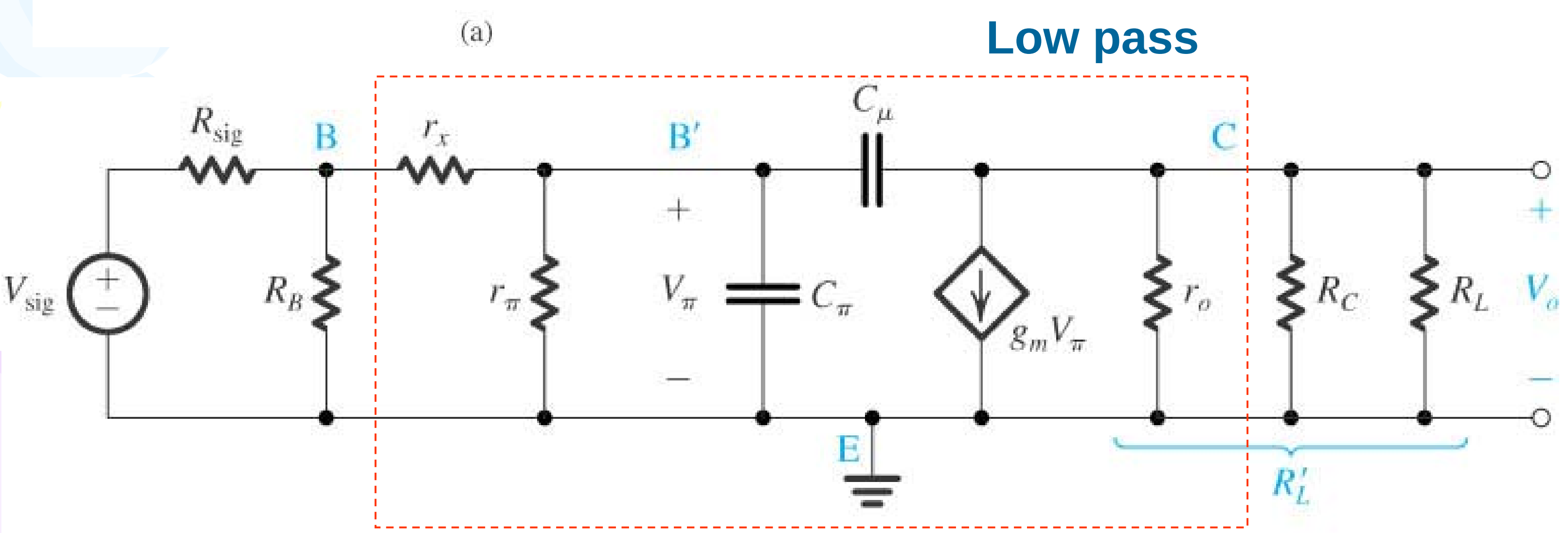
Unity-gain bandwidth

$$\omega_T \approx \omega_\beta \beta = \frac{g_m}{C_\pi + C_\mu}$$

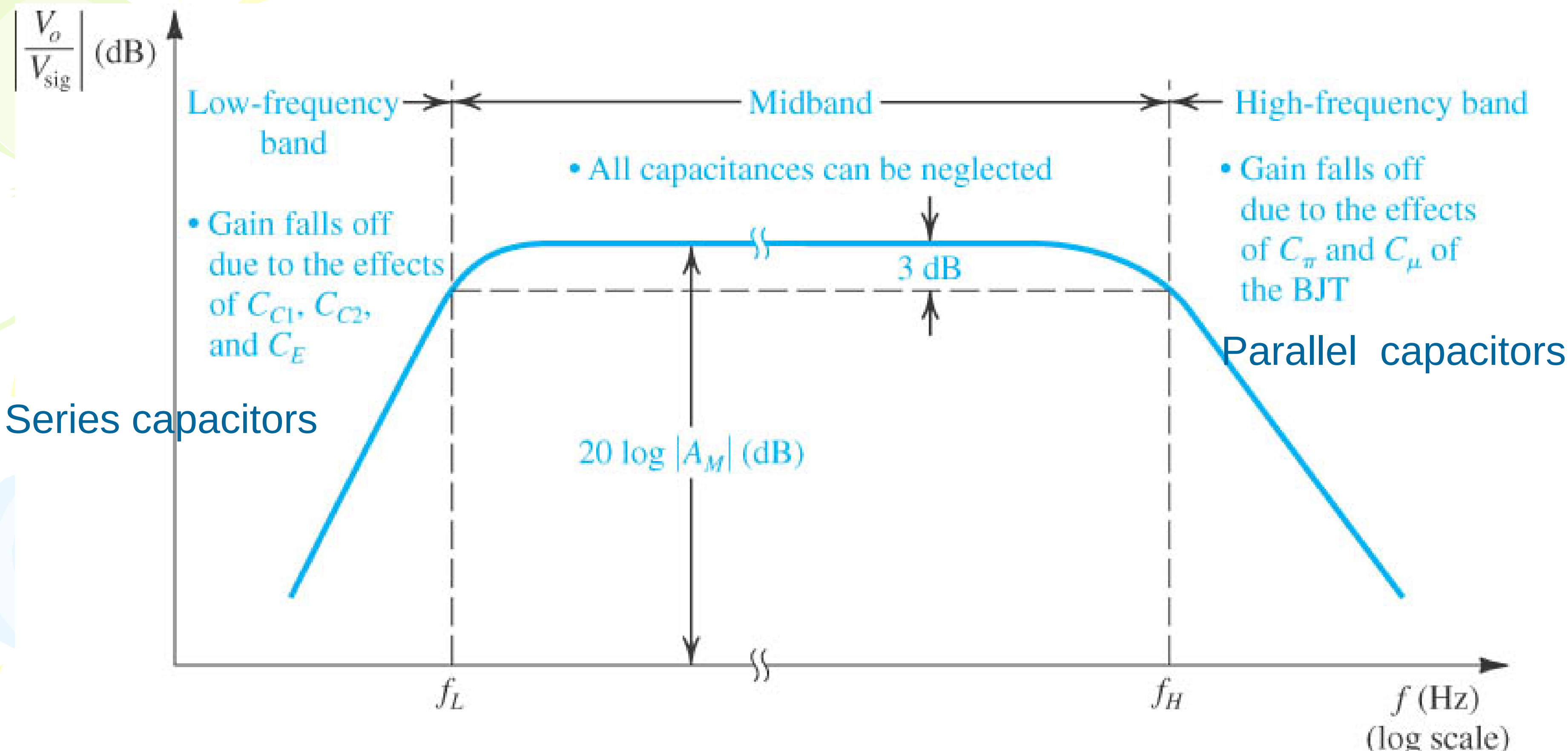
$$f_T = \frac{g_m}{2\pi(C_\pi + C_\mu)}$$

CE Amplifier





(a)

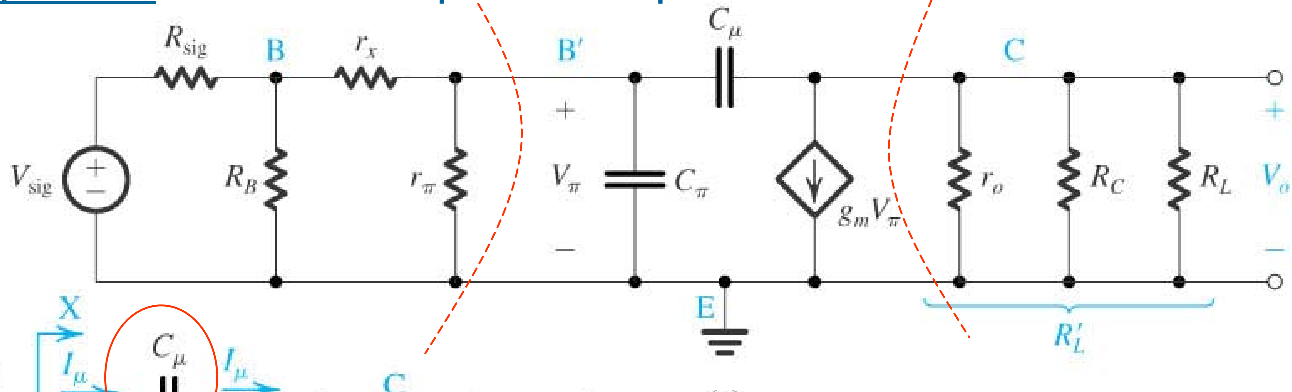


(b)

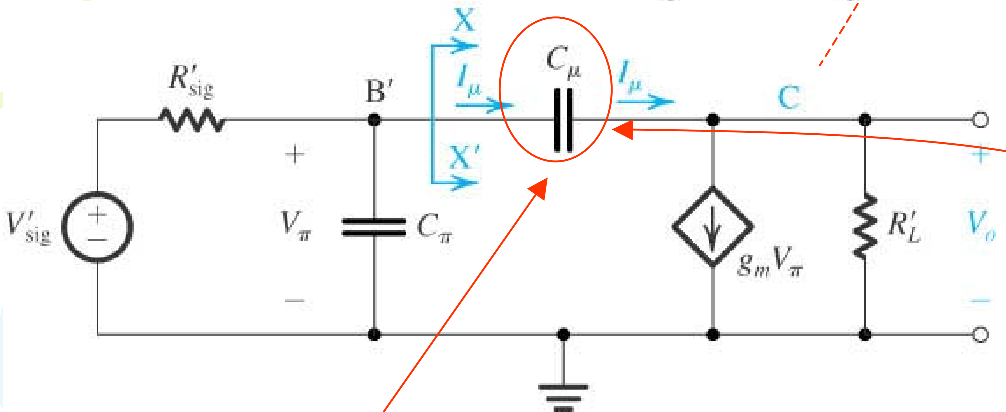
Bandwidth $$BW \equiv f_H - f_L \approx f_H (\because f_L << f_H)$$

Midband amplitude $$A_M = \frac{v_o}{v_{sig}} = -\frac{(R_B // r_\pi)}{(R_B // r_\pi) + R_s} g_m (r_o // R_C // R_L)$$

High frequency response: The effect of parallel capacitors



(a)



$$V'_{sig} = V_{sig} \frac{R_B}{R_B + R_{sig}} \frac{r_\pi}{r_\pi + r_x + (R_{sig} /\!/ R_B)}$$

$$R'_{sig} = r_\pi /\!/ [r_x + (R_B /\!/ R_{sig})]$$

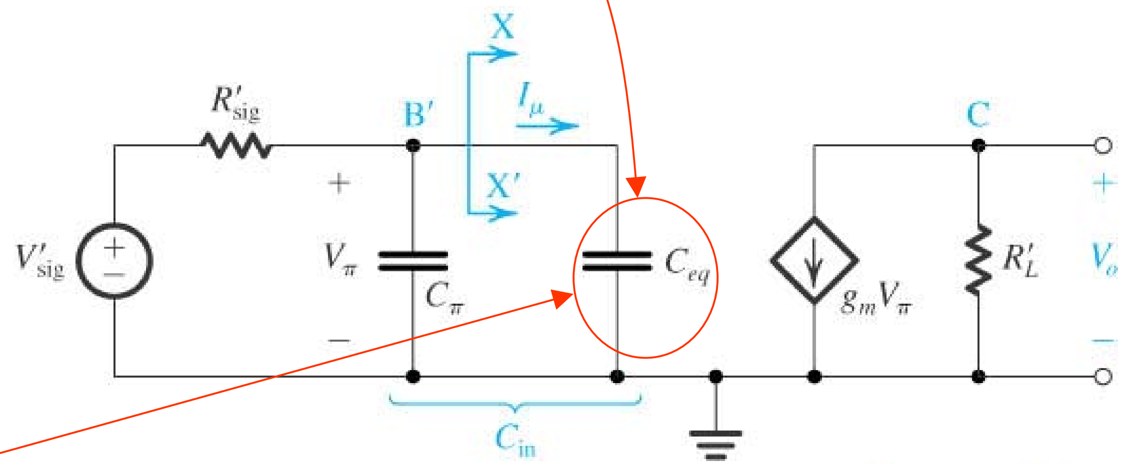
(b)

$$i_\mu = sC_\mu (v_\pi - v_o)$$

$$v_o = -g_m R_L' v_\pi$$

$$i_\mu = sC_{eq} v_\pi$$

$$C_{eq} = C_\mu (1 + g_m R_L')$$

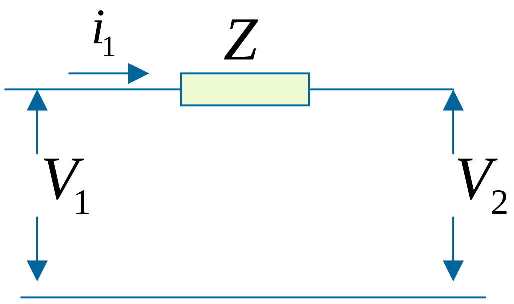


$$C_{in} = C_\pi + C_{eq} = C_\pi + C_\mu (1 + g_m R'_L)$$

$$V_o = -g_m R'_L V_\pi$$

(c)

Miller's theorem

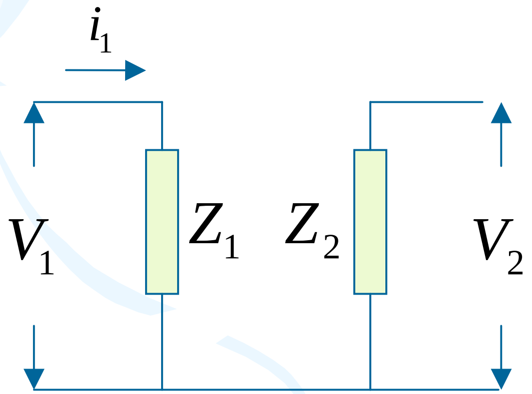


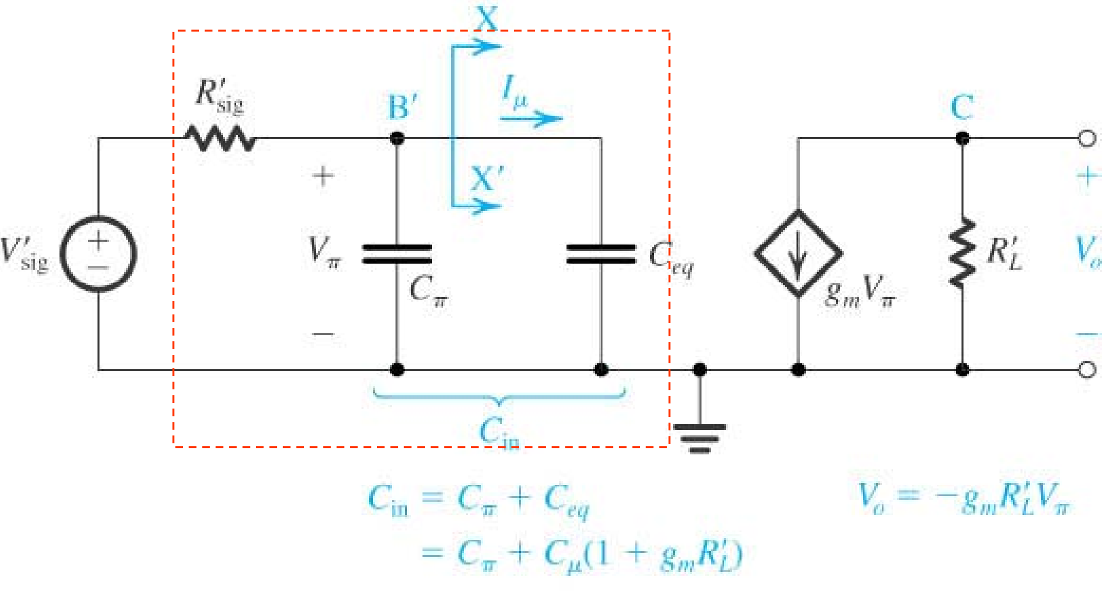
$$\boxed{\frac{V_2}{V_1} = k}$$

$$i_1 = \frac{V_1 - V_2}{Z} = \frac{V_1}{Z_1}$$

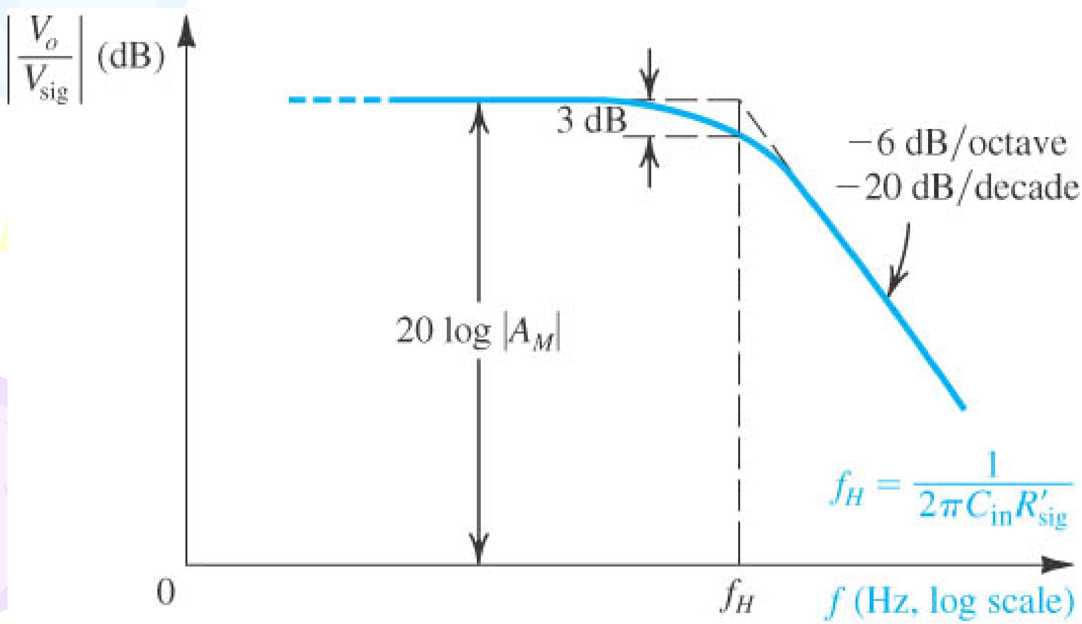
$$\frac{V_2}{V_1} = k \Rightarrow Z_1 = \frac{Z}{1-k}$$

$$Z_2 = \frac{k}{k-1} Z$$





(c)



(d)

$$v_\pi = v'_s \frac{1}{1 + (\frac{s}{\omega_0})}$$

$$\omega_0 = 1 \Big/ R'_s (C_\pi + C_{eq})$$

$$f_H = 1 \Big/ 2\pi R'_s (C_\pi + C_{eq})$$

$$C_{eq} = C_\mu \boxed{(1 + g_m R'_L)}$$

Miller multiplier

Example 5.18 Find the Midband gain and upper 3 dB frequency of CE amplifier.

The parameters of Hybrid π model

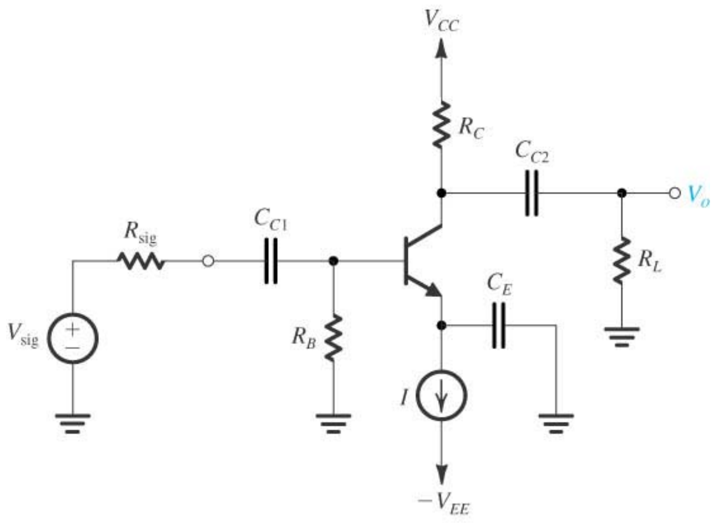
$$g_m = \frac{I_C}{V_T} = 40mA/V$$

$$r_\pi = \frac{V_T}{I_B} = 2.5k\Omega$$

$$r_o = \frac{V_A}{I_C} = 100k\Omega$$

$$C_\pi + C_\mu = \frac{g_m}{\omega_T} = 8pF = C_\pi + 1$$

$$C_\pi = 7pF$$



(a)

$$V_{CC} = V_{EE} = 10V$$

$$I = 1mA$$

$$R_B = 100k\Omega, R_C = 8k\Omega$$

$$R_s = 5k\Omega, R_L = 5k\Omega$$

$$\beta = 100, V_A = 100V$$

$$C_\mu = 1pF, r_x = 50\Omega$$

$$f_T = 800Mhz$$

$$A_M = \frac{v_o}{v_{sig}} = -\frac{R_B}{R_B + R_s} \frac{r_\pi}{(R_B // R_s) + r_\pi + r_x} g_m (r_o // R_C // R_L) = -39$$

$$C_{eq} = C_\mu (1 + g_m R_L^{'})$$

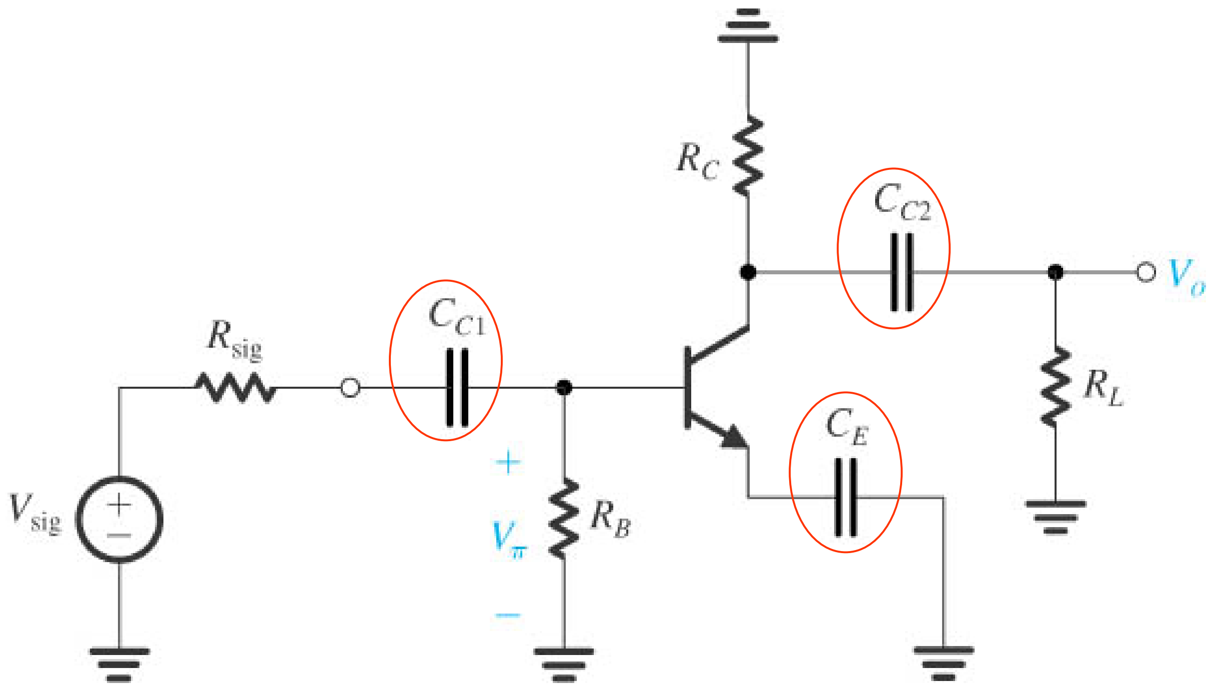
$$C_{in} = C_\pi + C_{eq} = 128\, pF$$

$$R_s^{'} = r_\pi //[r_x + (R_B // R_S)] = 1.65 k\Omega$$

$$\omega_0 = 1 \Big/ R_s^{'}(C_\pi + C_{eq})$$

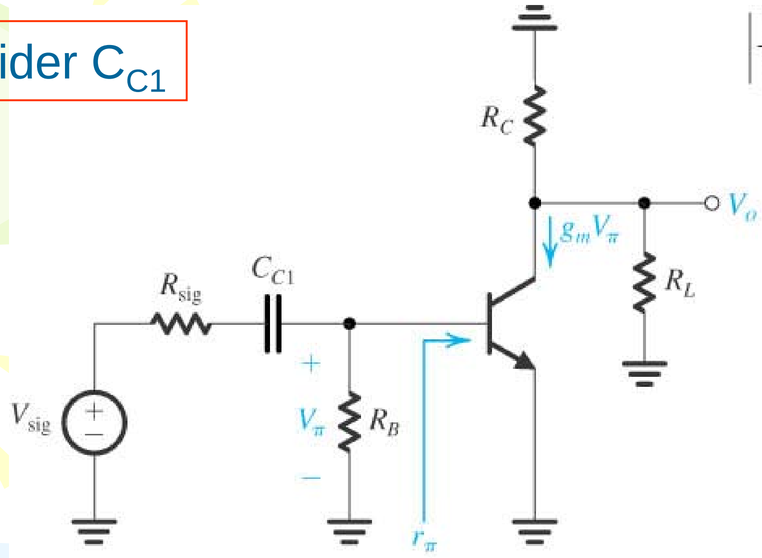
$$f_H = 1 \Big/ 2\pi R_s^{'}(C_\pi + C_{eq}) = 754 kHZ$$

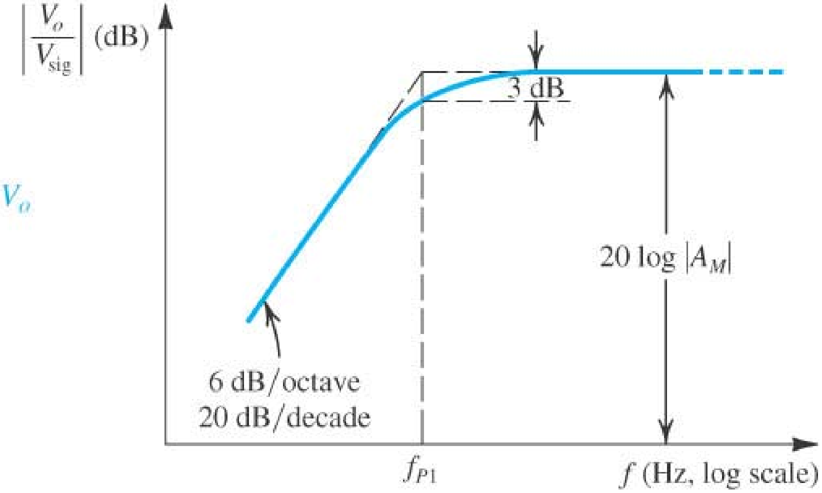
Low frequency response: The effects of the series capacitors



(a)

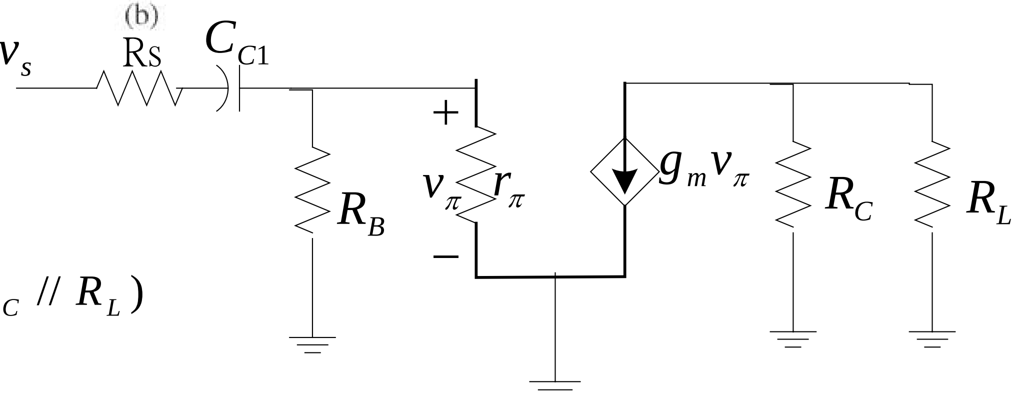
Consider C_{C1}





$f_{P1} = 1/2\pi C_{C1}[(R_B // r_\pi) + R_{sig}]$

(b)



$$v_\pi = v_s \frac{R_B // r_\pi}{(R_B // r_\pi) + R_s + \frac{1}{sC_{C1}}}$$

$$v_o = -g_m v_\pi (R_C // R_L)$$

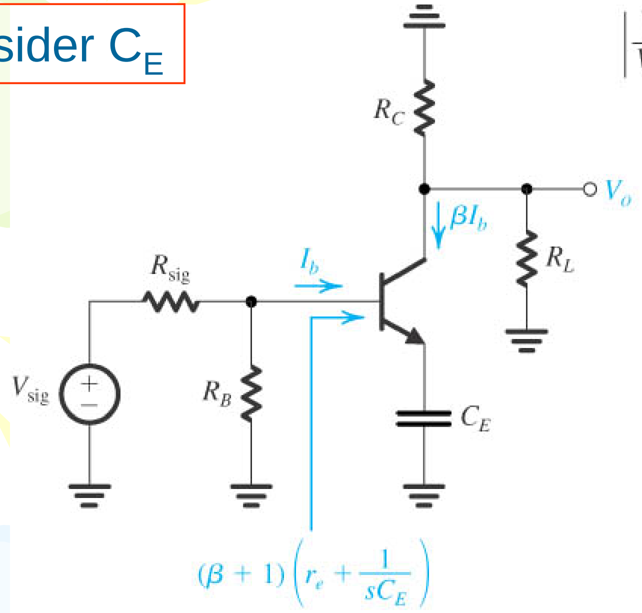
$$\frac{v_o}{v_s} = \frac{-(R_B // r_\pi)}{(R_B // r_\pi) + R_s + \frac{1}{sC_{C1}}} g_m (R_C // R_L)$$

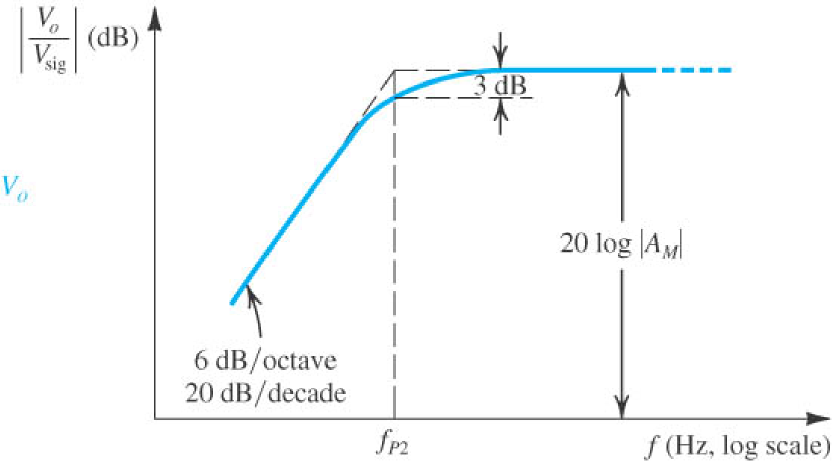
$$= g_m (R_C // R_L) \frac{-(R_B // r_\pi) sC_{C1}}{sC_{C1}[(R_B // r_\pi) + R_s] + 1}$$

$$= -g_m (R_C // R_L) \frac{(R_B // r_\pi)}{[(R_B // r_\pi) + R_s]} \left\{ \frac{s}{s + \frac{1}{C_{C1}[(R_B // r_\pi) + R_s]}} \right\}$$

$$\omega_{p1} = \frac{1}{C_{C1}[(R_B // r_\pi) + R_s]}$$

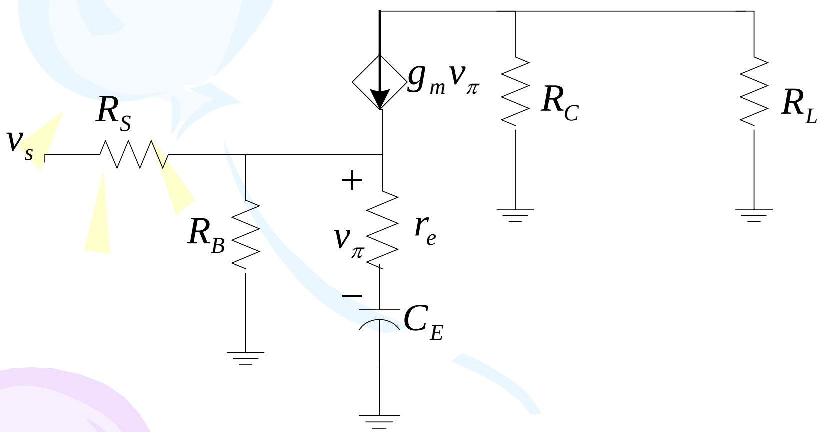
Consider C_E





$$f_{P2} = 1/2\pi C_E\left[r_e + \frac{R_B /\!/ R_{sig}}{\beta+1}\right]$$

(c)



$$I_b = v_s \frac{R_B}{R_B+R_s}\frac{1}{(R_B /\!/ R_s)+(\beta+1)(r_e + \frac{1}{sC_E})}$$

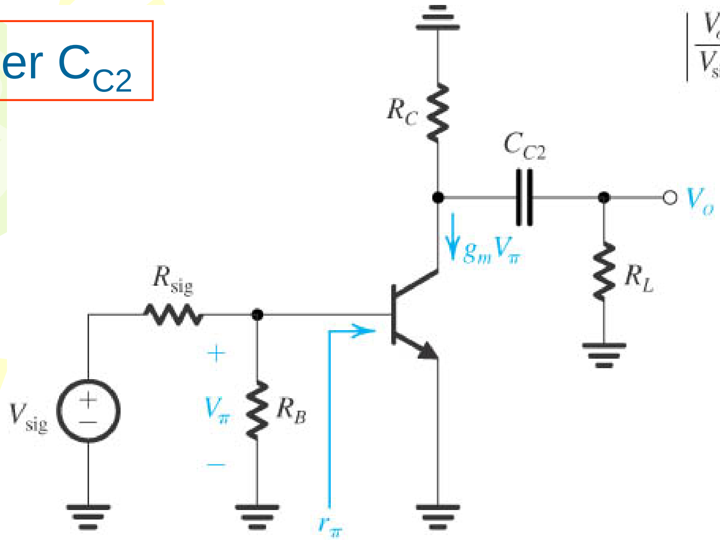
$$v_o = -\beta I_b (R_C /\!/ R_L)$$

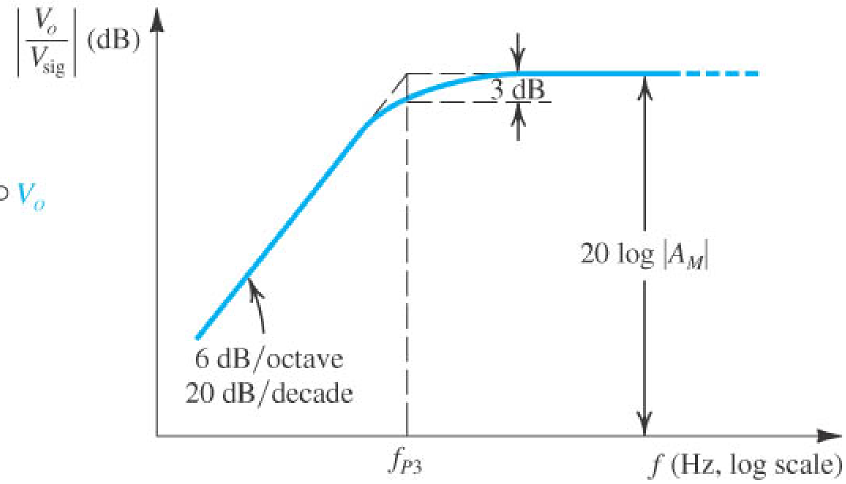
$$\frac{v_o}{v_s} = -\frac{R_B}{R_B+R_s}\frac{\beta(R_C /\!/ R_L)}{(R_B /\!/ R_s)+(\beta+1)(r_e + \frac{1}{sC_E})}$$

$$= -\frac{R_B}{R_B+R_s}\frac{\beta(R_C /\!/ R_L)}{(R_B /\!/ R_s)+(\beta+1)r_e}\left\{\frac{s}{s+\frac{1}{C_E[(\frac{R_B /\!/ R_s}{\beta+1})+r_e]}}\right\}$$

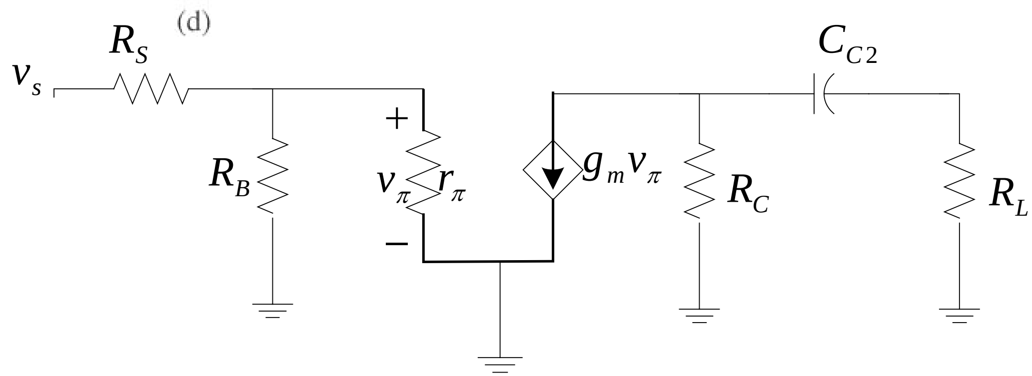
$$\omega_{p2} = \frac{1}{C_E[(\frac{R_B /\!/ R_s}{\beta+1})+r_e]}$$

Consider C_{C2}





$f_{P3} = 1/2\pi C_{C2}(R_C + R_L)$

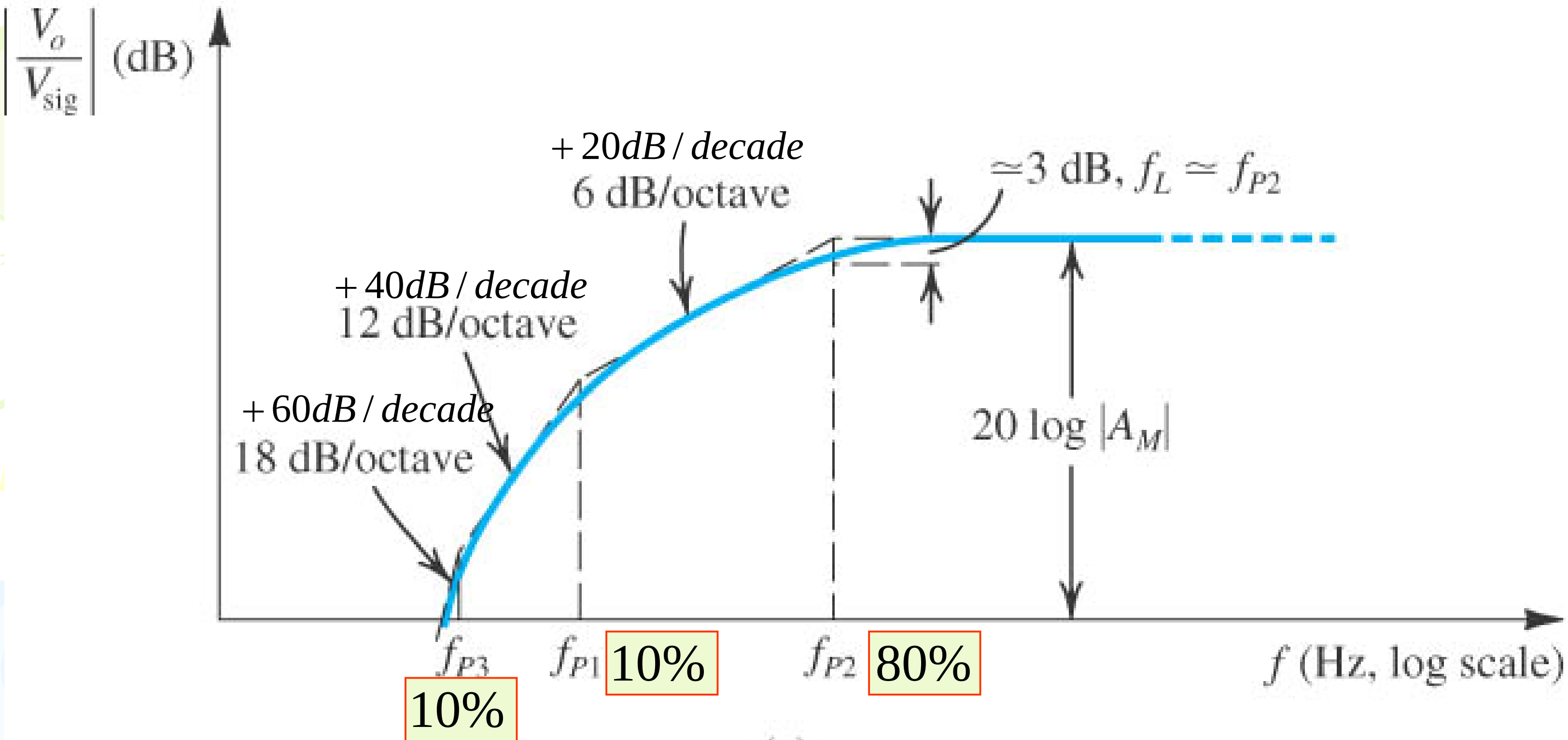


$$v_\pi = v_s \frac{R_B // r_\pi}{(R_B // r_\pi) + R_s}$$

$$v_o = -g_m v_\pi \frac{R_C}{R_C + R_L + \frac{1}{sC_{C2}}} R_L$$

$$\frac{v_o}{v_s} = \frac{-(R_B // r_\pi)}{(R_B // r_\pi) + R_s} g_m (R_C // R_L) \frac{s}{s + \frac{1}{C_{C2}(R_C + R_L)}}$$

$$\omega_{p3} = \frac{1}{C_{C2}(R_C + R_L)}$$



(e)

$$\frac{v_o}{v_s} = -A_M\left(\frac{s}{s+\omega_{p1}}\right)\left(\frac{s}{s+\omega_{p2}}\right)\left(\frac{s}{s+\omega_{p3}}\right)$$

$$\omega_{p1} = \frac{1}{C_{C1}[(R_B // r_\pi) + R_s]}$$

$\boxed{R_{C1}}$

$$\omega_{p2} = \frac{1}{C_E[(\frac{R_B // R_s}{\beta+1}) + r_e]}$$

dominant $\boxed{R_E}$

$$\omega_{p3} = \frac{1}{C_{C2}(R_C + R_L)}$$

$\boxed{R_{C2}}$

Example 5.19 Find the C_{C1}, C_{C2} and C_E the CE amplifier of the example 5.18.

$$V_{CC} = V_{EE} = 10V$$
$$I = 1mA$$
$$R_B = 100k\Omega, R_C = 8k\Omega$$
$$R_s = 5k\Omega, R_L = 5k\Omega$$
$$\beta = 100, g_m = 40$$
$$r_\pi = 2.5k\Omega$$
$$f_L = 100hz$$

$$\omega_{p1} = \frac{1}{C_{C1}[(R_B // r_\pi) + R_s]}$$

$$\omega_{p2} = \frac{1}{C_E[(\frac{R_B // R_s}{\beta + 1}) + r_e]}$$

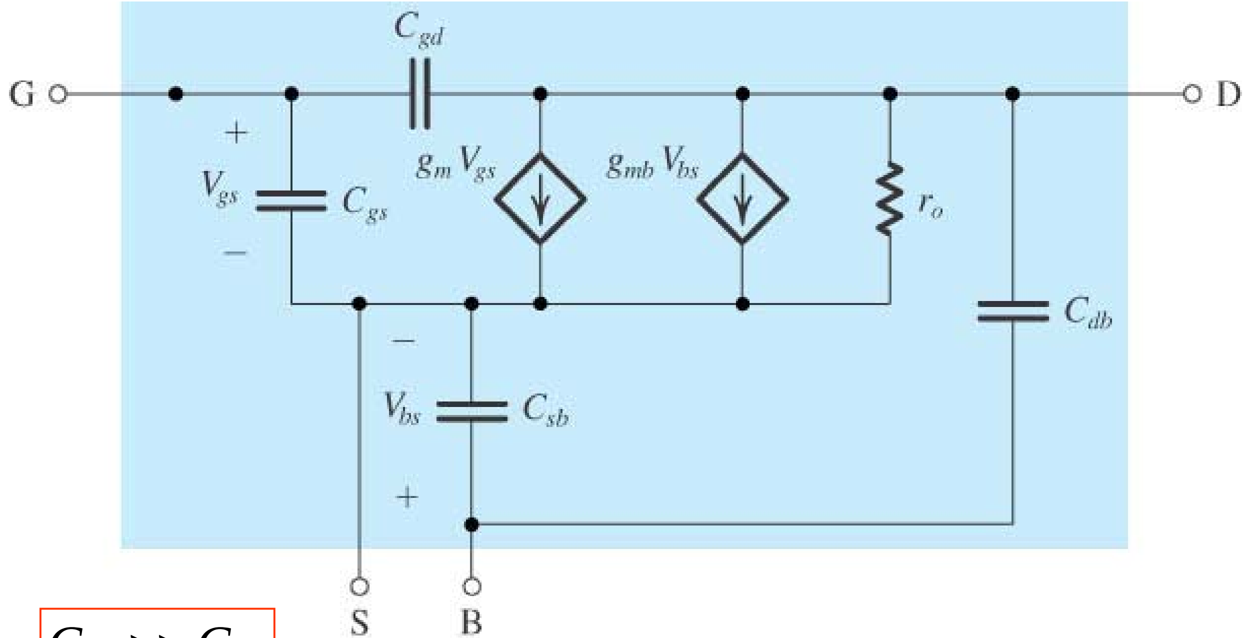
$$\omega_{p3} = \frac{1}{C_{C2}(R_C + R_L)}$$

$$C_E[(\frac{R_B // R_s}{\beta + 1}) + r_e] = 0.8 \times 2\pi f_L \Rightarrow C_E = 27.6\mu F$$

$$C_{C1}[(R_B // r_\pi) + R_s] = 0.1 \times 2\pi f_L \Rightarrow C_{C1} = 2.1\mu F$$

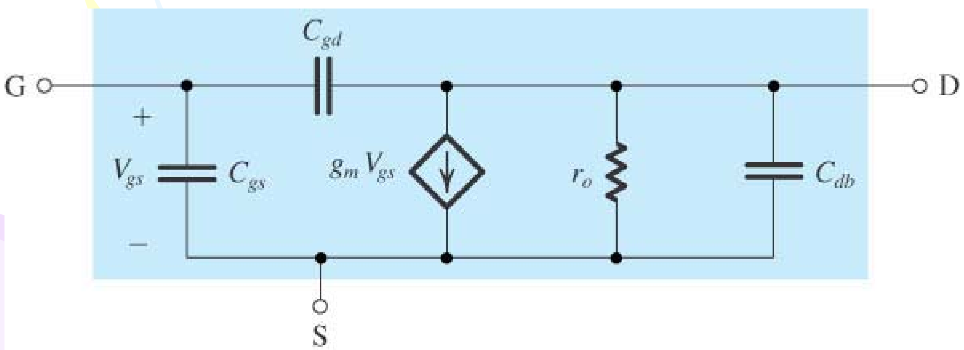
$$C_{C2}(R_C + R_L) = 2\pi\omega f_L \Rightarrow C_{C2} = 1.2\mu F$$

MOSFET high frequency model

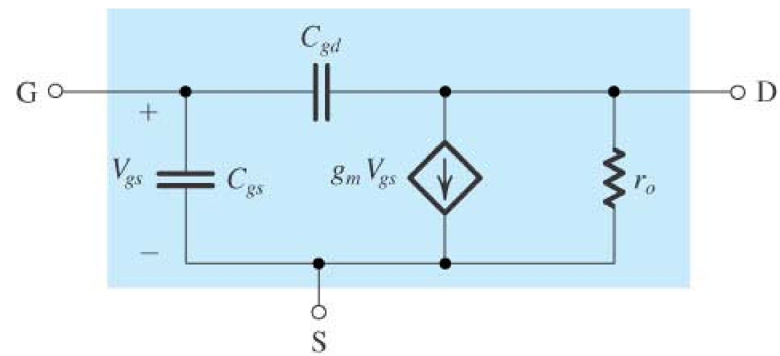


$$C_{gs} >> C_{gd}$$

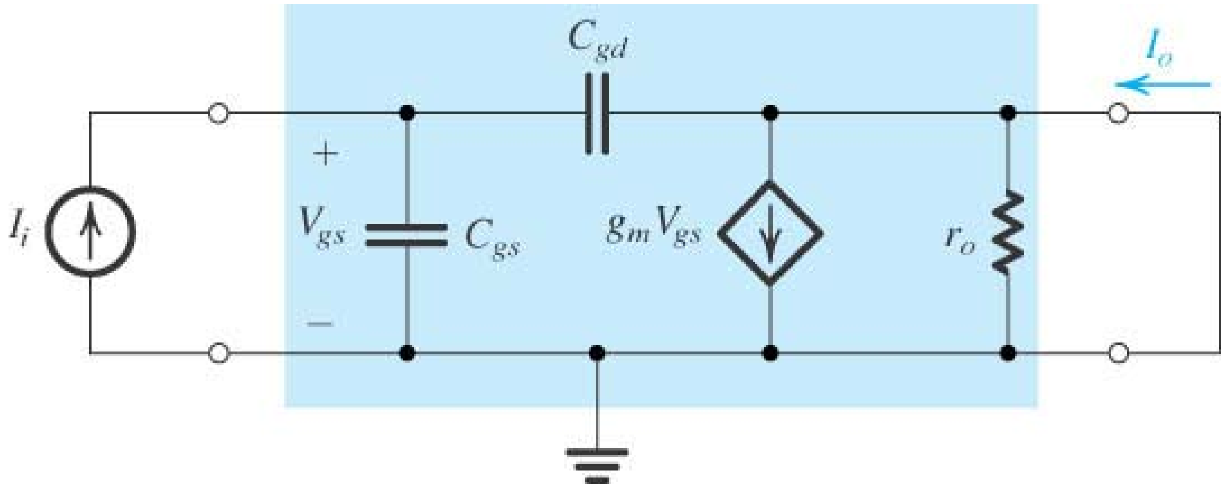
(a)



(b)



(c)



$$I_o = g_m v_{gs} - sC_{gd} v_{gs} \approx g_m v_{gs}$$

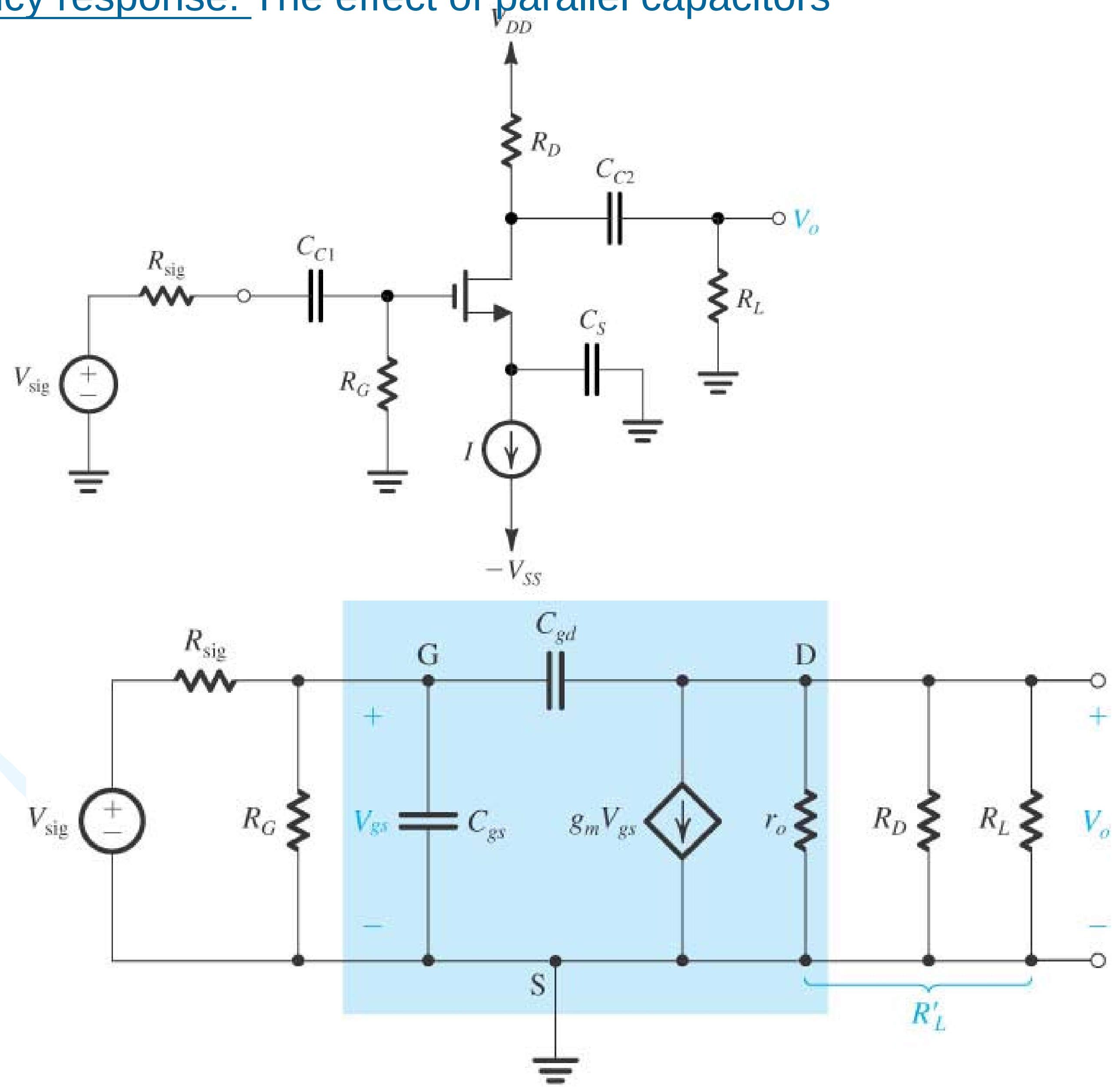
$$v_{gs} = \frac{I_i}{s(C_{gs} + C_{gd})}$$

$$\frac{I_o}{I_i} = \frac{g_m}{s(C_{gs} + C_{gd})} = \frac{g_m}{j\omega(C_{gs} + C_{gd})}$$

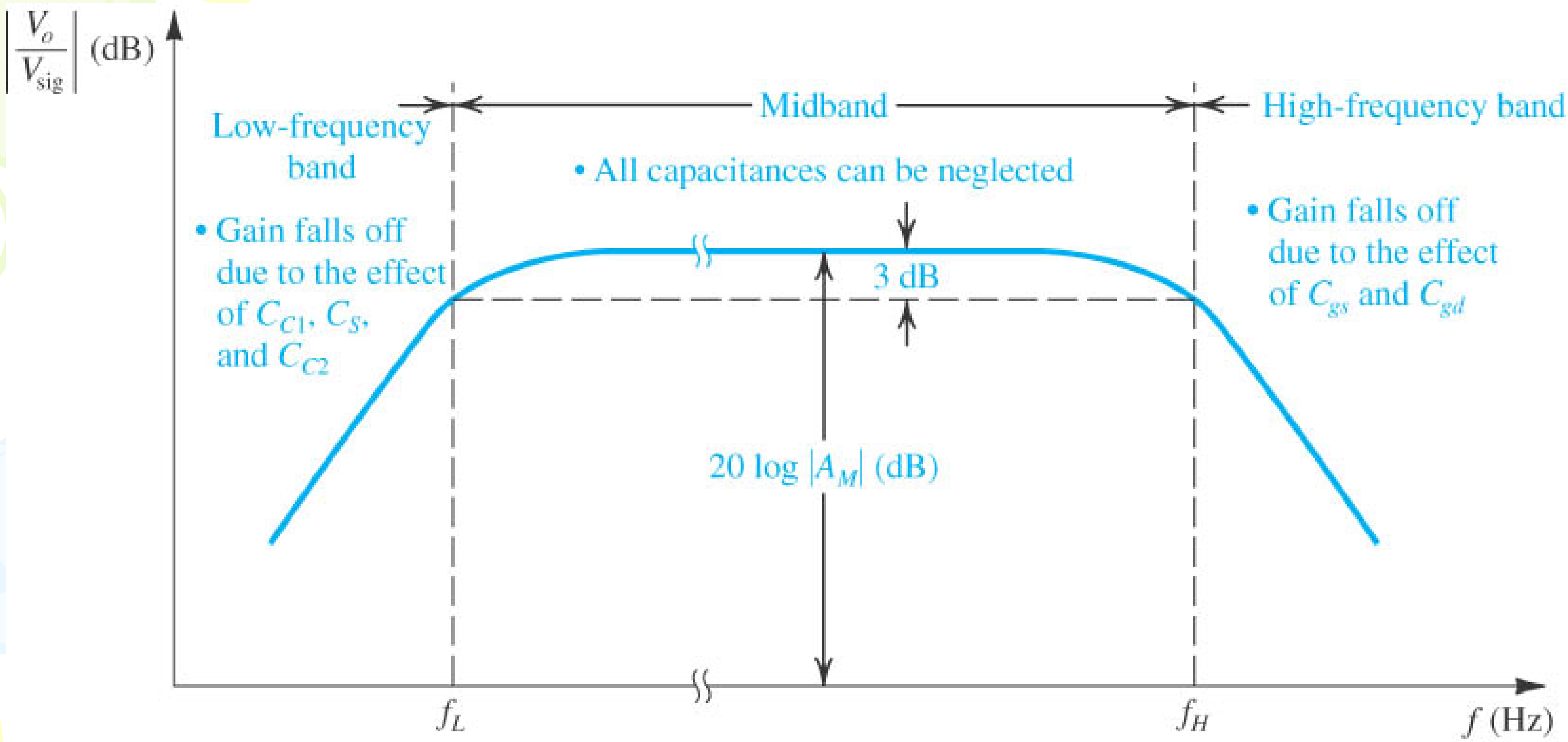
$$if \quad \omega = \frac{g_m}{(C_{gs} + C_{gd})} \Rightarrow \frac{I_o}{I_i} = 1 \Rightarrow 0dB$$

$$\boxed{\omega_T = \frac{g_m}{(C_{gs} + C_{gd})} \qquad f_T = \frac{g_m}{2\pi(C_{gs} + C_{gd})}}$$

High frequency response: The effect of parallel capacitors



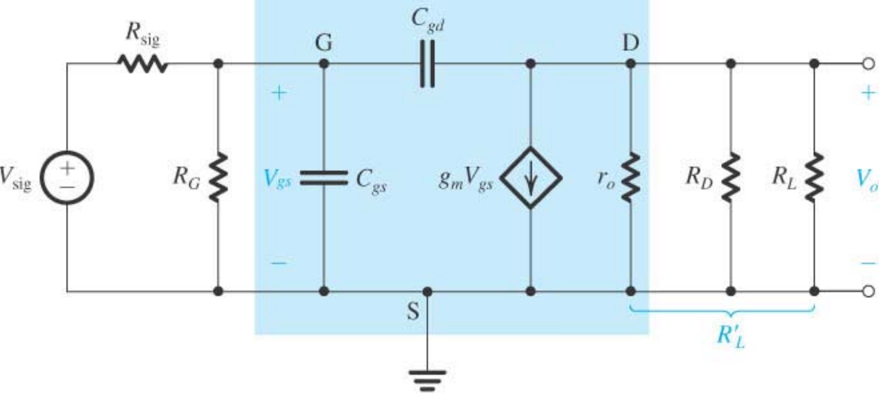
(a)



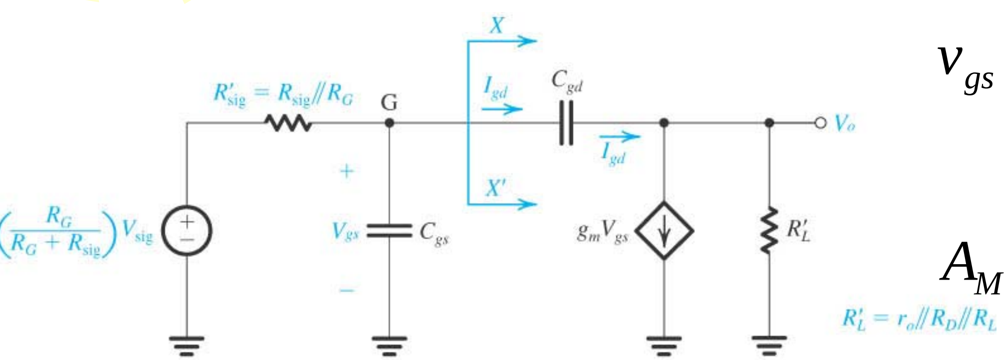
(b)

Bandwidth $BW \equiv f_H - f_L \approx f_H (\because f_L << f_H)$

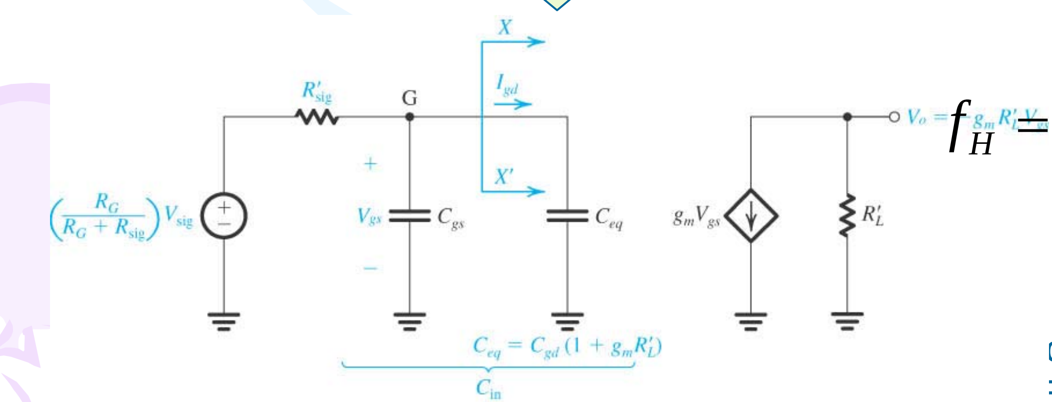
Midband amplitude $$A_M = \frac{v_o}{v_{sig}} = -\frac{R_G}{R_G + R_s} g_m (r_o // R_D // R_L)$$



(a)



(b)



(c)

$$I_{gd} = sC_{gd}(v_{gs} - v_o)$$

$$v_o \approx -g_m R'_L v_{gs}$$

$$I_{gd} = sC_{gd}(1 + g_m R_L^{'})v_{gs} = sC_{eq}v_{gs}$$

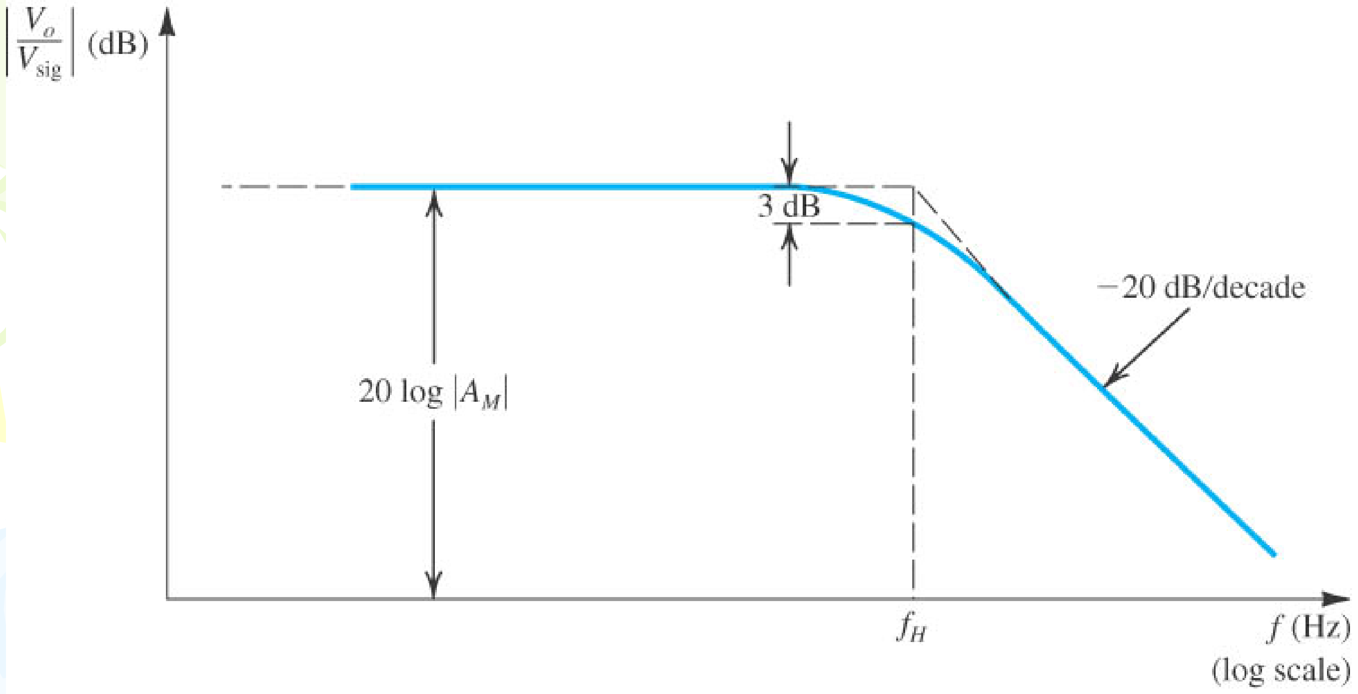
$$C_{eq} = C_{gd}(1 + g_m R_L^{'})$$

$$v_{gs} = \frac{R_G}{R_G + R_s} v_s \frac{1}{1 + s/\omega_0}$$

$$A_M = \frac{v_o}{v_s} = -\frac{R_G}{R_G + R_s} g_m R_L^{'}$$

$$\omega_0 = \frac{1}{RC} = \frac{1}{(R_G // R_s)[C_{gs} + C_{gd}(1 + g_m R_L^{'})]}$$

$$f_H = \frac{1}{2\pi (R_G // R_s)[C_{gs} + C_{gd}(1 + g_m R_L^{'})]}$$



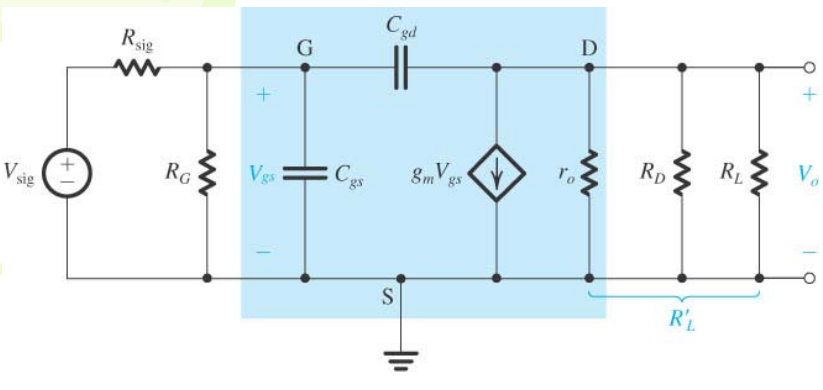
(d)

$$A_M = -\frac{R_G}{R_G + R_s} g_m R_L'$$

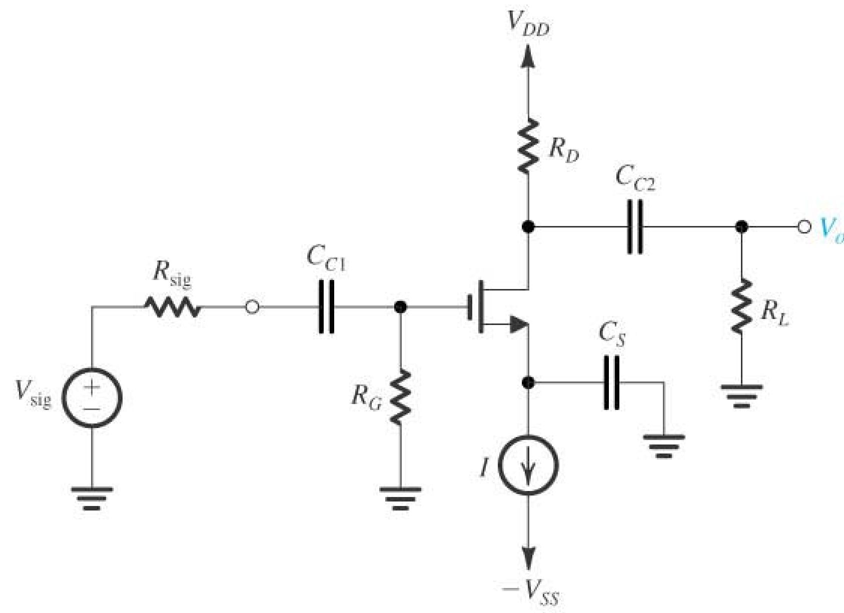
$$\omega_0 = \frac{1}{RC} = \frac{1}{(R_G // R_s)[C_{gs} + C_{gd}(1 + g_m R_L')]}$$

$$f_H = \frac{1}{2\pi(R_G // R_s)[C_{gs} + C_{gd}(1 + g_m R_L')]}$$

Example 4.12 Find the Midband gain and upper 3 dB frequency of CS amplifier.



(a)



(a)

$$A_M = -\frac{R_G}{R_G + R_s} g_m R_L^{'}$$

$$\omega_0 = \frac{1}{RC} = \frac{1}{(R_G // R_s)[C_{gs} + C_{gd}(1 + g_m R_L^{'})]}$$

$$f_H = \frac{1}{2\pi(R_G // R_s)[C_{gs} + C_{gd}(1 + g_m R_L^{'})]}$$

$I = mA$

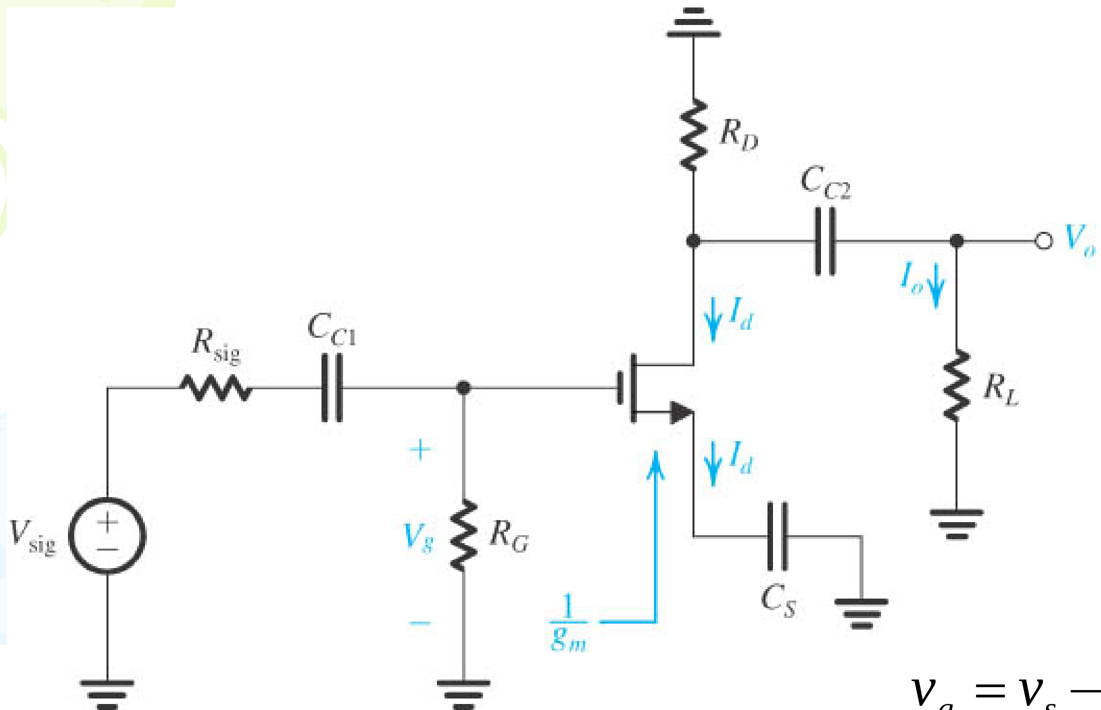
$R_S = 100k\Omega, R_G = 4.7M\Omega$

$R_D = 15k\Omega, R_L = 15k\Omega$

$g_m = 1, r_0 = 150k\Omega$

$C_{gs} = 1pF, C_{gd} = 0.4pF$

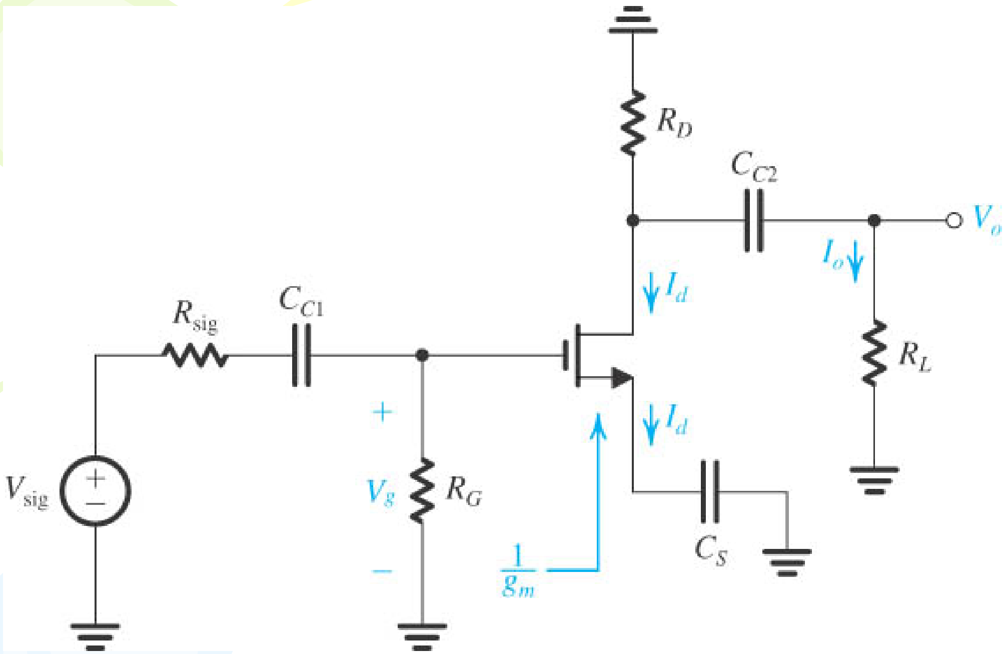
Low frequency response: The effects of the series capacitors

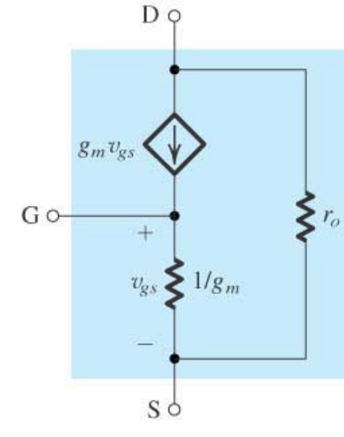


$$v_g = v_s \frac{R_G}{R_G + \frac{1}{sC_{C1}} + R_s}$$

$$v_g = v_s \frac{R_G}{R_G + R_s} \frac{s}{s + \frac{1}{C_{C1}(R_G + R_s)}}$$

$$\omega_{p1} = \frac{1}{C_{C1}(R_G + R_s)}$$





(a)

$$i_d = \frac{v_g}{1/g_m + 1/sC_s}$$

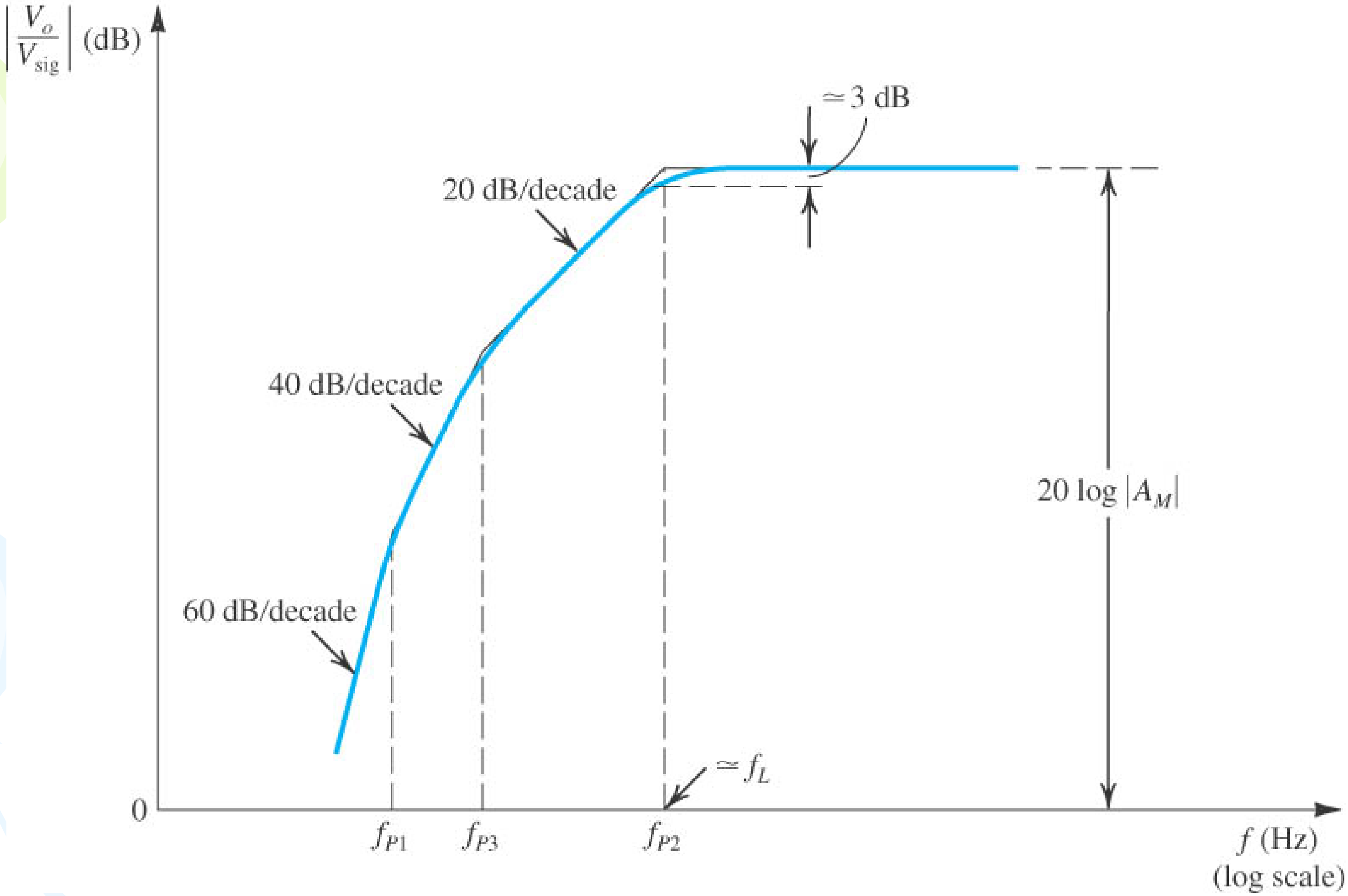
$$= g_m v_g \frac{s}{s + g_m/C_s}$$

$$\omega_{p3} = g_m/C_s$$

$$i_o = -i_d \frac{R_D}{R_D + 1/sC_{C2} + R_L}$$

$$v_o = i_o R_L = -i_d (R_D // R_L) \frac{s}{s + 1/C_{C2}(R_D + R_L)}$$

$$\omega_{p2} = 1/C_{C2}(R_D + R_L)$$



$$\omega_{p1} = 1 \Big/ C_{C1}(R_G + R_s)$$

$$\omega_{p3} = 1 \Big/ C_{C2}(R_D + R_L)$$

$$\omega_{p2} = g_m \Big/ C_s$$

$$\frac{v_o}{v_s} = -\frac{R_G}{R_G + R_s} g_m (R_D // R_L)\left(\frac{s}{s+\omega_{p1}}\right)\left(\frac{s}{s+\omega_{p2}}\right)\left(\frac{s}{s+\omega_{p3}}\right)$$

Example 4.13 Find the C_{C1}, C_{C2} and C_s the CS amplifier of the example 4.12.

$$f_L = f_{p2} = \frac{1}{2\pi\left(C_s / g_m\right)}$$

$$\Rightarrow C_s = \frac{g_m}{2\pi f_L} = 1.6\mu F$$

$$f_{p1} = 10Hz = 1 / 2\pi C_{C1}(R_G + R_s)$$

$$\Rightarrow C_{C1} = 1 / 2\pi f_{p1}(R_G + R_s) = 3.3nF$$

$$f_{p3} = 10Hz = 1 / 2\pi C_{C2}(R_D + R_L)$$

$$C_{C2} = 1 / 2\pi f_L(R_D + R_L) = 0.53\mu F$$

$$I = mA$$

$$R_S = 100k\Omega, R_G = 4.7M\Omega$$

$$R_D = 15k\Omega, R_L = 15k\Omega$$

$$g_m = 1$$

$$C_{gs} = 1pF, C_{gd} = 0.4pF$$

$$f_L = 100Hz$$

$$f_{p1} = f_{p3} = \frac{100Hz}{10}$$